TOWARD ASSESSING THE SENSITIVITY OF BUILDINGS TO CHANGES IN CLIMATE

Semester Project

Masters of Energy Management and Sustainability

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Abstract

A building is designed for one set of typical climatic conditions. In the context of expected climate change, substantial numbers of existing and new buildings are expected to survive long enough to experience perceptible shifts in climate 'normals' (averages). This is problematic for predicting building performance, largely because the exact nature of climate change is hard to predict with certainty. Thus an optimal design is not only tuned to the original design conditions, but is also robust to changes in climatic conditions in the sense of a low sensitivity of its performance.

To predict a building's response to changes in typical weather, two inputs are required: weather data representing this change, and suitable metrics to compare building performance across different climate normals. This report presents initial work on a proposed method for assessing the sensitivity of new or existing buildings to climate change. This method begins with a selection of weather files to represent climate change, then quantifies a building's passive performance in those climates using an enthalpy-based metric, and ends with a graphical analysis of the performance of the building in different climates to assess its robustness. In this report, we propose an objective performance metric based on the extent to which a building creates indoor conditions passively, i.e. without auxiliary systems. Initial work suggests that the performance assessment carried out here is reproducible and applicable for indoor environment design and evaluation in different ranges of climate change. This approach enables a comparison of building performance without the bias introduced by inherent differences in climatic conditions.

Contents

Chapter 1

Introduction

Despite all the controversy surrounding climate change prediction, there is some agreement that the pace of climate change will be fairly rapid in the not-too-distant future, even if there is less agreement about what that change will be. There is also general agreement that the built environment, as a major user of energy (de Wilde and Coley, 2012), is contributing to the problem. As building designers, we are not trying to predict climate change, only what it means for the buildings we construct. Rightly or wrongly, a lot of research has focused so far on mitigation of climate change rather than adaptation to it. Buildings are usually designed for a functional lifespan of 50-100 years, with some level of anticipated renovation. External economic pressures remaining the same, the lifespan of a building strongly depends on its ability to maintain a desirable indoor climate. A building that does not meet expectations is liable to be torn down as soon as it is feasible to do so.

If buildings are to perform well, i.e. maintain a comfortable indoor environment, in a climate different from the one they were designed for, we need to know their robustness or sensitivity to changes in typical weather or climate. The sustainability of a building is heavily dependent on its lifespan, since the environmental costs of materials and construction must be amortized over as many years as possible. Good design for the present weather is no guarantee of performance in a different climate, since individual design features and components behave differently when subjected to varying kinds of environmental stress. Current predictions of the robustness of the "more energy efficient building variants [are mixed]: Crawley (2008) states that they are less sensitive to change [than regular buildings], whereas Wang et al. (2010) come to the opposite conclusion." (de Wilde and Coley, 2012)

This report describes the initial development of a methodology to assess the robustness of a building's performance in a changing climate. It consists of three parts: a performance metric based on the concept of an enthalpy 'distance' or 'gap' to compare building performance across different climatic conditions and building types, a protocol for selecting files to simulate future weather conditions, and finally a graphical method for assessing the robustness of a building to changes in climate. Since the methodology is in its initial phases of development, the number of case studies is limited. The graphical analysis is made from a relative perspective, comparing case studies to one another in terms of their correspondence to physical phenomenon. A proper quantification of the shapes of the resulting graphs (which we call '*response curve*') is expected to be carried out in future work.

1.1 Performance metric

The performance of buildings is usually expressed in terms of such metrics as energy use, if they have auxiliary HVAC systems, or number of (un)comfortable hours (Crawley, 2008; DesignBuilder, 2011b). They are complementary as a higher use of active *Heating, Ventilation and Air Conditioning* (HVAC) will lead to a higher energy consumption and less uncomfortable hours. These metrics are perfectly valid for capturing the performance of a building in a given climate to explore design options, or to compare the performance of different buildings in the same climate.

However, these comparisons rely on starting from the same baseline – the prevailing climate and its particular effect on a building. If the baseline itself shifts during the course of an analysis, then the resulting figures for energy use or discomfort hours are less informative about the performance of the building itself. Rather, they are colored by the inherent nature of the climate and its relation to human comfort. To put it bluntly, a building will not (and should not) use the same amount of energy in Mumbai, Chicago, and Berlin. Therefore it is necessary to develop performance metrics which measure performance as the ability of the passively acting building substance to mitigate outdoor climatic conditions into more comfortable indoor conditions.

This idea of a shifting baseline has been explored in other contexts as the idea of a '*climatic energy burden*'. Emmanuel et al. (2013) carried out a review of historical and recent efforts to quantify this climate burden. They themselves proposed a *Climate Energy Index* (CEI), which is very similar to one component of the performance metric proposed in this report, the '*outdoor energy distance*' (detailed in section 2.2.1). They calculate the CEI as "an annual sum of unit energy required to condition [i.e. sensible and latent load] $1m^3$ of air at any weather hourly ordinate to the nearest boundary of a human comfort zone" (ISO 7730 in this case).

1.2 Future weather data

Guan (2009) reviewed extant methods to create future weather data for building simulation. She classified these methods into four main types: extrapolating statistical (refs. 1-3 in Guan, 2009) and imposed offset methods (refs. 6-13 in Guan, 2009), where historical patterns are mapped to average anticipated changes in stochastic weather models; or stochastic weather (refs. 15-16 in Guan, 2009) and global climate models (GCM) (refs. 17-18 in Guan, 2009), which localize our understanding of the underlying physics and statistical properties of the climate. de Wilde and Coley (2012) also mention the possibility of using historical data from other locations to represent climate change for a given (home) location, and this is the approach adopted in this paper. Since future climate cannot, by definition, be compared to measurements, evaluating these methods against each other is problematic. Their representativeness may, for example, be compared with climate change projections from the Inter-governmental Panel on Climate Change (IPCC). Their spatial and temporal resolution is important, as is the time required to generate them for a given location.

To produce hourly weather files for simulation, one can use any of the extant procedures for creating Design Reference Years from long term data. Examples of projects include those for specific applications (e.g. McLeod et al. (2012) for Passivhaus design and Crawley (2008) for Urban Heat Island issues) or those for specific geographical areas (e.g. the Prometheus project based on the UKCP'09 predictions (Eames et al., 2010; University of Exeter, 2013)). Software such as *METEONORM* (Remund et al., 2012b) generate 'future weather files' corresponding to IPCC climate change scenarios. However, it is not transparent how these files are produced. Since this software relies on stochastic generation of hourly data from observed distributions of different parameters scaled by long term 'normals' (averages), it probably generates future weather data by extrapolation of these normals based on a chosen scenario. In this project, we used hourly weather files from the *METEONORM* software based on historical data.

1.3 Future weather in building simulation

Several projects have explored the practicality of using probabilistic climate projections in building simulation (Jenkins et al., 2011; Kershaw et al., 2011; Shamash et al., 2012; Tian and de Wilde, 2011). The general trend seems to be to cover as many probable scenarios as possible without a computational overload of thousands of simulations. Since computationally-intensive and comprehensive risk analyses are not feasible for industrial application, various simplifying measures have been proposed (e.g regression equations (Patidar et al., 2011; Patidar et al., 2012a; Patidar et al., 2012b) or pre-selection of future typical weather years (Kershaw et al., 2011)). Due to the limited number of simulations of the three investigated buildings in different climatic conditions, the sample size of the resulting data is small. This is one of the issues which have to be taken into account when discussing the results.

In this project, the metrics and processes to assess the sensitivity of a building's performance to changes in climatic conditions are combined to a methodology. The development and evaluation of this methodology is the research objective of this project. By applying the developed methodology to three building types designed for different locations a validation is conducted and first results are collected and discussed.

Chapter 2

Methodology

The last semester's project resulted in preliminary methods to characterize the distance of climatic states towards a fixed comfort zone, to characterize a building's performance and to characterize the difference between climatic conditions. This project builds on those results by refining them and applying them in the measurement of climatic robustness of buildings. The methodology, which is equally applicable for new or existing buildings, consists of the following steps:

1. Simulate a building in its home environment (call it location *A*), with or without an HVAC system. In this study we removed HVAC systems to understand the buildings' passive response.
2. Locate contours of temperature gradients around the home location (or any other pivotal weather parameter of interest). For example, cities with a one degree centigrade difference in mean annual temperature (locations $B_1, B_2, ..., B_n$), and so on (two degree centigrade difference: C_{1-n},three degree centigrade difference: D_{1-n}, ...). See Figure 2.1.
3. Simulate sub-sample of locations at each contour $(B, C, D, ...)$ of interest, preferably with a variety of humidity and solar radiation patterns.
4. Plot simulation output of interest ('performance') against the pivotal parameter. In this initial study, we plot a building's passive performance (in terms of the '*enthalpy distance difference*' defined in section 2.2) against temperature increments.

2.1 Future weather

It is problematic to predict the complete set of future values and interactions for a given climate (Guan, 2009). In this method, we bypass the question of the predictive accuracy and suitability of future climate generation with a speculative approach. We hypothesize a temperature change and simulate several geographical close locations with that difference of temperature, but an otherwise different climate.

Locations for comparison are chosen by using high-resolution temperature maps. In those maps 'contour' lines of a specified temperature difference are drawn (see Figure 2.1). By choosing locations on or close to those lines, the fixed temperature difference (factor of interest) ensures a sufficient distinction while still having a set of different climatic conditions (humidity, seasonality, etc.).Thus, we do not restrict ourselves to a particular prediction and consider various probable developments. We use existing weather files from different locations in the vicinity of the home location. This allows us to examine the passive response of a building as the hypothetical future climate changes by increments of a chosen parameter. In this case we picked outdoor mean annual dry bulb temperature as our pivotal parameter, although any parameter of interest could be used instead.

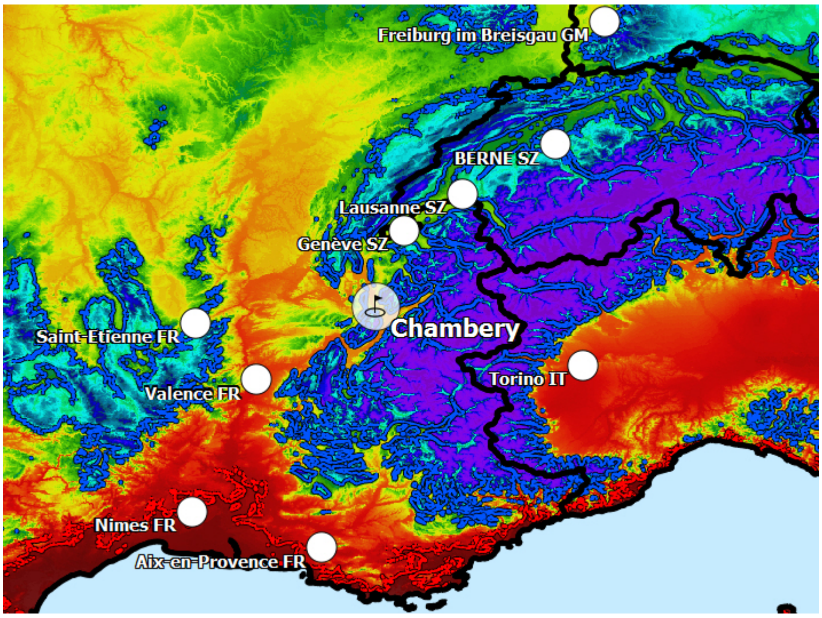

Figure 2.1: The temperature contour map for Chambéry.

Figure 2.1 shows contour lines for a mean annual temperature +2.5°C (red) and -2.5°C. The home location Chambéry has a mean annual temperature of 11,1°C.

2.2 Performance metric

The most commonly used metrics to evaluate a building's performance are its energy consumption and/or the number of (un)comfortable hours (based on some arbitrary comfort zone). These are complementary metrics, since a higher use of energy is generally associated with a climate that will also produce a high number of uncomfortable hours. Energy consumption is, however, highly dependent on the predominant outdoor conditions and the HVAC system used (type, efficiency, etc.). This means that the comparison of buildings in different climates or with different HVAC systems is not straightforward. Furthermore, the behavior of a building's design and materials is masked in such a comparison. In this project, we used a metric which measures performance as the ability of a building, acting passively and without an auxiliary system, to mitigate the impacts of outdoor climatic conditions.

Performance in this understanding describes the extend to which the building moves climatic conditions into the human comfort zone. This approach depends on two definitions: the definition of the comfort zone to which the distance of the occurring outdoor and indoor climatic values are measured and the definition of how this distance is measured. Outdoor climatic data is taken from the weather file of the location in question. Indoor climatic data results from the hourly simulation of the investigated building type in the same location.

2.2.1 Definiton of distance

During the work of the previous semester project, the distance of a climatic state, defined by humidity and temperature, was measured using the concept of heating and cooling degree days (HDD, CDD) (Christenson et al., 2006; Grondzik et al., 2009). *Heating degree days* are derived from the difference between a base temperature from which on a building needs to be heated and the average daily temperature. This

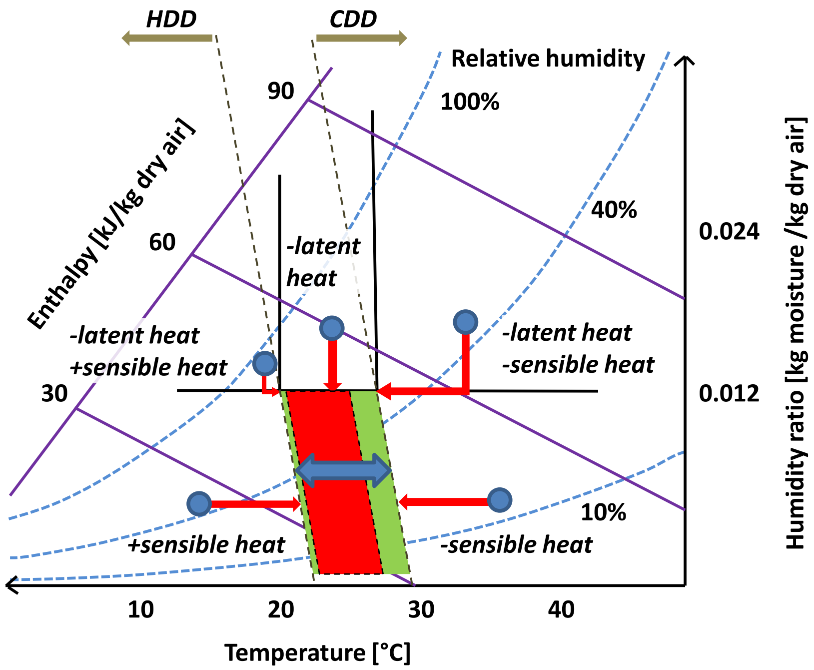

Figure 2.2: The concept of the idealized enthalpy distance is represented here by the arrows moving from a circle (indoor/outdoor conditions) to the parallelogram (which represents a comfort zone). It is plotted on a simplified Psychrometric Chart.

temperature difference is multiplied with the respective duration of this condition. This metric is used as an estimation for the heating demand in a specific climate (Grondzik et al., 2009). In the previous project the humidity dependent edge temperature of the comfort zone was taken as the base temperature. On this basis the distance to the hourly values surrounding the comfort zone was calculated in terms of degree hours (see Figure 2.2: *heating degree days* - HDD on the left edge of the comfort zone and *cooling degree days* - CDD on the right edge of the comfort zone).

The metric developed in this project is conceptually similar to heating and cooling degree days. The disadvantage of the degree day approach is that it measures the distance to the comfort zone only in one dimension – temperature. It is unable to capture the distance between over-humid climatic states and the upper humidity limit of the comfort zone. This is illustrated in Figure 2.2 as the gap over the comfort zone between HDD and CDD. In contrast, the notion of enthalpy offers the possibility of describing the location of each point around the comfort zone in two dimensions.

Enthalpy is a measure of the total energy in the air and defined as the sum of sensible and latent heat in the air. Whereas sensible heat describes the energy content of the air due to its temperature, latent heat expresses the energy content due to its amount of moisture. The concept of enthalpy offers the possibility to calculate the energy required to move a climatic state from one condition (defined by humidity and temperature) to any other condition (Harriman, 2002). Thus, the enthalpy required to move any uncomfortable state into the comfort zone can be taken as a metric for its distance to the comfort zone. In order to make the transition from enthalpy to the more tangible concept of energy, enthalpy has to be multiplied with the mass of air of the respective zone.

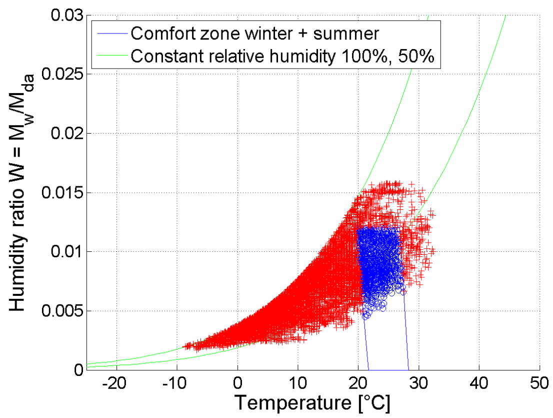

Figure 2.3: Cloud of hourly **outdoor** climatic states for Chambéry. The humidity ratio is given in mass water per mass dry air.

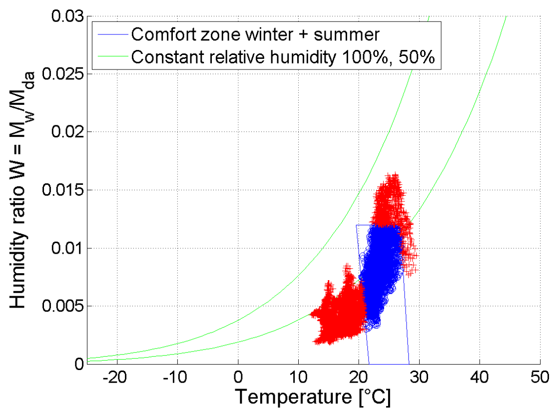

Figure 2.4: Cloud of hourly **indoor** climatic states for Chambéry. The humidity ratio is given in mass water per mass dry air.

The metric proposed in this paper represents the difference between two quantities: the enthalpy distances of indoor and outdoor conditions from a given comfort zone[1]. Indoor climatic conditions are obtained from simulating a building without an HVAC system. The outdoor and indoor states can be plotted on a psychrometric chart as 'clouds' of points (see Figures 2.3 and 2.4). The distance between individual points in these clouds and a specific comfort zone is what we call the *enthalpy distance* of each point. This is, in essence, the theoretical sum of latent and sensible energy addition/removal required to 'move' a point into the comfort zone. We chose to not calculate a straight-line distance, since HVAC systems and human comfort models treat sensible and latent energy differently (see Figure 2.2). The performance metric we report is the difference of the sums of outdoor and indoor enthalpy distances for each hour of the year. This idealized concept is illustrated in the change between Figure 2.3 and Figure 2.4. The magnitude of the contraction of the 'cloud' of climatic states by the passively acting building is exactly what the *enthalpy distance difference* calculates.

The *indoor enthalpy distance* is representative of expected HVAC energy use, as demonstrated by Figure 2.5. Figure 2.5 shows that simulated HVAC (heating) energy use correlates closely with the *indoor enthalpy distance*. The *indoor enthalpy distance* is calculated from simulation results of a free running version of the same building. Using this metric has the advantage over actual simulated HVAC consumption of not being dependent on set-points or efficiencies and that additional simulation runs with an implemented HVAC system are not required. Thus, *indoor enthalpy distance* can be used in the following as a proxy for the metric of HVAC energy consumption to which the developed *enthalpy distance difference* performance metric can be compared.

2.2.2 Definition of the comfort zone

In the previous semester project the comfort zone was defined as the combined zone of comfort in summer and winter cloth as defined in the graphical method for typical indoor environments in ASHRAE (2004). The comfort zone as depicted in figure 5.2.1.1 in ASHRAE (2004) (Figure 2.6) is derived from the combinations of air temperature and humidity for which the PMV (Predicted Mean Vote) is within a range of $-0.5 < PMV < +0.5$ with assumptions made for wind speed, metabolic rate and clothing level. For this range the occupant acceptability is determined to be 80%. For the calculations in the previous

[1] Treated here as the change in sensible and latent energy per unit volume (Harriman, 2002). We do not consider the chemical energy of the air.

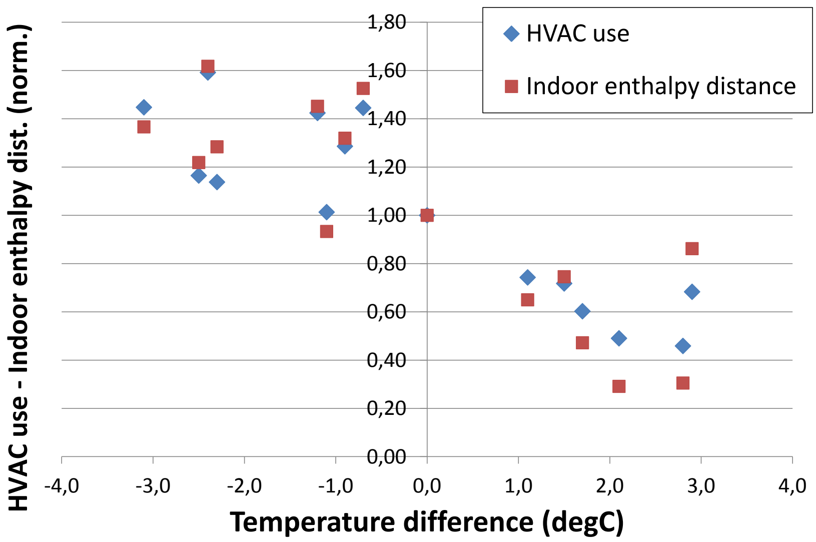

Figure 2.5: *Indoor enthalpy distance* and HVAC energy use plotted against temperature change for Chambéry.

project the comfort zone was assumed to be the same for the whole year. The software *DesignBuilder* uses such a constant comfort zone with 0.5 Clo (clothing) in summer and 1.0 Clo in winter to calculate the number of uncomfortable hours (Comfort analysis in DesignBuilder, 2011a).

In this project, comfort is taken to be adaptive but in the boundaries of the previously described standard ASHRAE winter and summer comfort zones. In keeping with the adaptive comfort approach originally developed by Dear and Brager (1998), and later adopted by the the ANSI/ASHRAE Standard 55-2004 (review in Halawa and Hoof, 2012)(ASHRAE, 2004), the comfort temperature is assumed to depend linearly on the preceding month's mean temperature.

$$comfort - temperature \quad [^{\circ}C] = 18.9 + 0.255 * ET_{out} \tag{2.1}$$

ET$_{out}$ is the running mean monthly temperature previous to the day in question. The adaptive comfort chart (Dear and Brager, 1998) gives only a range of acceptable temperatures around the calculated comfort temperature and neglects humidity (see Figure 2.7). In order to make the connexion between the adaptive comfort chart and the comfort zone model, the calculated comfort temperature is taken as the center of

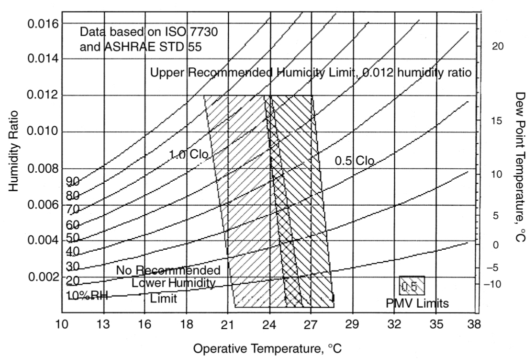

Figure 2.6: ASHRAE comfort chart used for most applications as depicted in Figure 5.2.1.1 in ASHRAE (2004).

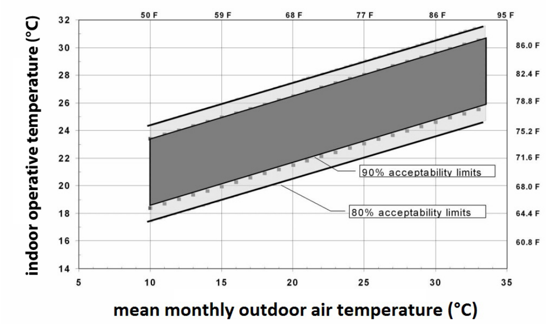

Figure 2.7: ASHRAE comfort chart used for naturally conditioned spaces as depicted in Figure 5.3 in ASHRAE (2004).

Table 2.1: Parameters for simulation.

Parameter	1 - CHM	2 - RDP	3 - BS
ASHRAE Climate	4A	1B	5C
Floors	2	2	3
Un / conditioned Area (m^2)	101/96	58/179	0/311
Wall U-val. ($W/m^2 - K$)	0.108	2.224	0.907
Win. U-val. ($W/m^2 - K$)	0.78	1.96	1.96
Window-Wall Ratio (%, South / Overall)	71/25	3/15	20/15

a moving comfort zone. This comfort zone is moving between the extremes of summer clothes and winter clothes. We chose a standard definition of comfort since it is not the main emphasis of this project. The idea of an adaptive comfort zone is appropriate to this analysis since we are simulating naturally ventilated residential buildings (Roaf et al., 2010). To examine the quantities generated by our metric against existing performance metrics, this report presents in the following chapter 3 the results of a comparison with discomfort hours, *indoor enthalpy distance* (theoretical HVAC loads) and *degree days*.

2.3 Simulation / Experiment

For our pilot case study we simulated three single family homes (Figure 2.8) in the towns of Braunschweig in north-central Germany (BS); Chambéry in south-eastern France (CHM); and Rudrapur in north-central India (RDP). The first two buildings are in continental European climates and the last is in a hot and humid monsoon climate. While the homes in Germany and India are real buildings, the building in France is a theoretical high performance design. Table 2.1 summarizes the important parameters for the three buildings. We selected the two real buildings because we had detailed data available about each and because they are sufficiently different in their construction and home climate.

To simulate a high performance building, we created a design for Chambéry based on specifications for the IBPSA modeling competition 2013, because it is close enough to Braunschweig to serve as a useful comparison. This kind of building is interesting for two reasons. Firstly, research has not conclusively decided if this building type has a higher sensitivity or is, in the contrary, more robust (Crawley, 2008; Wang et al., 2010). Secondly, the methodology and metrics are tested on an unusual building in the sense that it relies heavily on natural ventilation and nearly needs no HVAC system at all. This specific building has a predefined geometry and activity schedules as defined for the IBPSA modeling competition 2013. We assumed that the houses have four occupants each, and similar standard schedules and average internal heat gains from lights and appliances. The occupants open the windows to maintain an average 0.6 air-changes per hour (ACH), or when the temperature reaches 23.4°C.

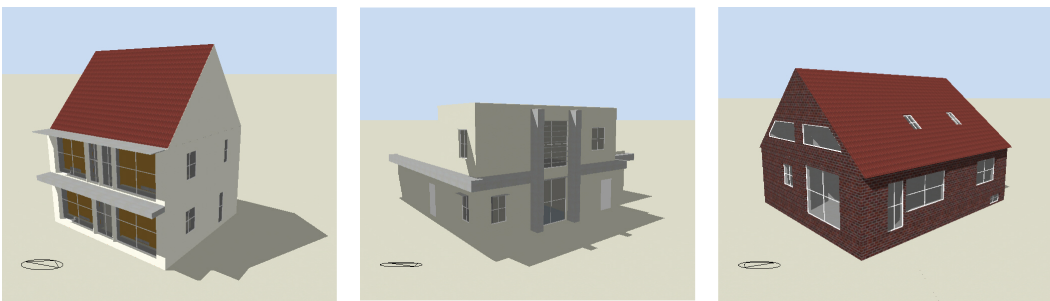

Figure 2.8: Renderings of the three buildings, from left to right: Chambéry, Rudrapur, Braunschweig.

Chapter 3

Results and discussion

3.1 Assessment of climate robustness

A high performance building can be hypothesized to lie at the peak of its response curve at its home climate. Performance (y-axis) is plotted over the change in mean annual temperature (x-axis). That means its performance should drop or stay the same in all surrounding locations. However, the slope of this drop is not guaranteed. If the performance decreases steeply the building is very climatically sensitive, and if the slope is gentler, the building is more robust. But many buildings are not optimally tuned to their location, which may place the peak of their response curve off-center (i.e. in another city). Nevertheless, it is still possible to forecast the building's sensitivity to changes in mean annual temperature.

Figures 3.1, 3.2, and 3.3 give an overview of the results obtained while applying different performance metrics. Figure 3.2 is a plot of the *indoor enthalpy distances* rather than HVAC energy use, since enthalpy distance is an idealized measure of the theoretical loads that an HVAC system would have to meet. These can be treated as equivalent metrics, as discussed in section 2.2.1. The sample size is small and trends are subject to a low coefficient of determination. In any case, our preliminary understanding of the behavior of our performance metric and its comparison with comfortable hours and HVAC energy use is discussed below.

The number of uncomfortable hours (Figure 3.1) and the HVAC energy requirement (Figure 3.2) do not give conclusive results. In both graphs, RDP shows no discernible trend whereas CHM and BS show an overall negative slope (increase of energy use and uncomfortable hours for falling temperatures and vice versa). These graphs are normalized and so do not show that the overall magnitudes of uncomfortable

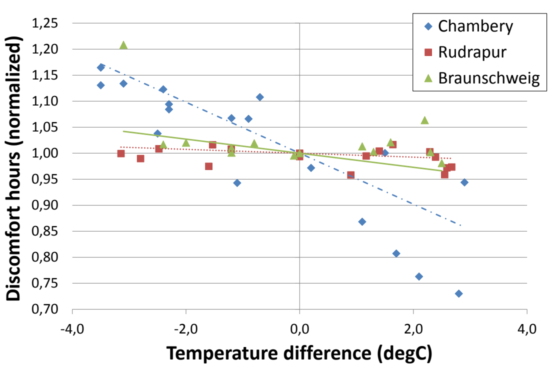

Figure 3.1: Normalized change in uncomfortable hours vs temperature change. The dashed line is for Rudrapur, solid for Braunschweig, and dashed-dotted for Chambéry.

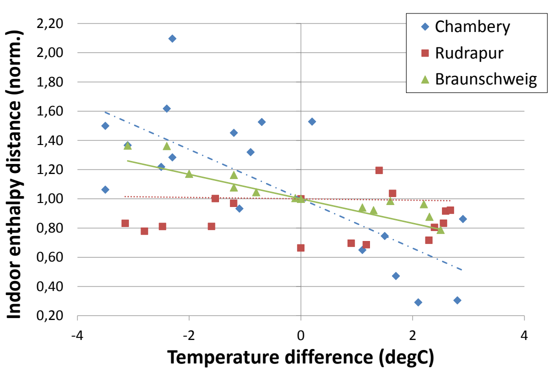

Figure 3.2: Normalized *indoor energy distance* vs temperature change.

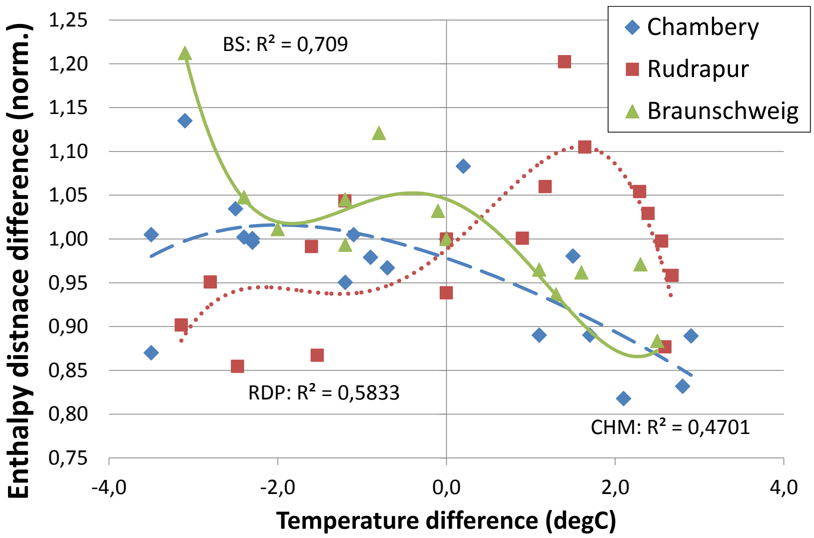

Figure 3.3: Normalized performance vs temperature change. R-squared: Coefficient of determination for 4th polynomial fit, see Appendix A.2 for equations

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hours are much higher for RDP and BS (about 6000) than CHM (about 2500), which is expected since they are real buildings which were not highly optimized in the design phase. In any case, we are more interested in changes rather than absolute numbers at this point. These graphs show a somewhat counter-intuitive result, on two counts. Firstly, the highly optimized building is not peaking in its home climate. And, secondly, its performance seems to be worse in a slightly colder climate (i.e. increase in uncomfortable hours and theoretical energy use). Evidence from recent heat-waves in continental Europe and North America would suggest the opposite. The very features that make a building retain heat to maintain warmer indoor temperatures during cold spells should cause it to overheat during warmer spells.

Looking at the curves of our performance metric (Figure 3.3), however, we see that the optimized building (CHM) and the BS building do peak in a way at their design locations. Trendlines are calculated as a 4th polynomial fit. Chambéry and Paris, which have nearly the same mean annual temperature, show both a higher (Paris) or equal performance than the surrounding locations for the Chambéry building. A peaking performance means for Chambéry that it lies at the inflection point of the curve. Performance is dropping for warmer climates and staying constant for colder climates. If the performance is decreasing or increasing below -2°C cannot be concluded due to the wide spread of data. An inflection point indicates a peaking performance as Figures 3.1 and 3.2 have shown that the general trend means a higher performance for colder climates. The Chambéry building is more sensitive to an increase in mean annual temperature than a decrease, which is due to the fact that the design optimization mainly focused on increasing passive solar gain. This resulted in a large glazing fraction on the southern facade. Similarly, the BS building has a peaking performance for its home location in the form of a local maximum. The steeper slopes of the 'standard' BS building indicate that it is more sensitive to changes in climatic conditions. The high performance building shows overall smaller gradients and thus a higher robustness.

We are also able to see general trends between the CHM, BS and RDP buildings. The cold climate buildings (CHM and BS) show negative slopes, which seems intuitive. If a building has been designed for cold climates, it is likely to continue performing well for small decreases in temperatures, though the effects are not straightforward. For a building with average insulation and solar harvesting potential, the effectiveness of the design seems to be enhanced with larger temperature gradients (between indoor and outdoor temperatures). In contrast, for the highly optimized building, performance does not improve dramatically since. This could be because the optimized building is already exploiting passive measures as much as possible, so it leaves little scope for improvement. However, the insulation and air tightness that serve the cold climate buildings well for a colder climate cause performance to drop when average outdoor temperatures rise. The cold climate designs are optimized to reduce heating demand by allowing in more sunlight and retaining heat, and they cannot do the opposite (i.e. reject/remove heat) when temperatures rise.

The reverse is true for the hot climate building (RDP), which has less insulation, more shading, and more thermal mass (due to a largely concrete-based construction). Colder conditions decrease performance, whereas warmer conditions increase performance up to a certain point, which is a logical result as the building is designed for a hot climate. The performance of the building drops off after a certain temperature increase. This could be because the building's indoor temperatures exceed the comfortable limits with enough frequency and severity to generate cooling demand (the building is overheated). As the metric measures the difference in enthalpy distance between indoor and outdoor conditions, a decrease in performance means that the cooling requirement indoors is increasing more than the heating requirement is decreasing.

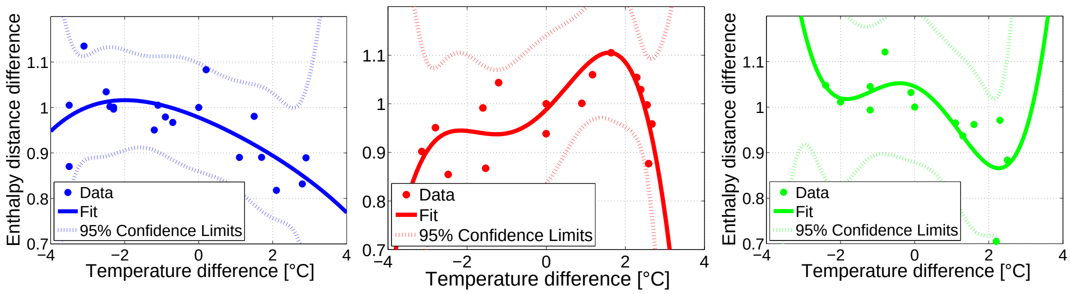

Figure 3.4: Normalized *Enthalpy distance difference* with polynomial fit and 95% confidence interval, from left to right: Chambéry n = 19, Rudrapur n = 17, Braunschweig n = 14.

3.2 Evaluation of performance metrics

The above analysis focused on the comparison of results obtained when applying three different performance metrics in the calculation of performance for the three investigated case studies. Discomfort hours, HVAC use and *enthalpy distance difference* were compared regarding their suitability to evaluate the sensitivity of the three building types to changing climatic conditions. In the following details of these performance metrics and their development are presented and evaluated.

Figure 3.3 shows a wide spread of data points for each temperature difference. This is expected and even desirable, since the selection of multiple locations at each temperature increment represents the variety of possible climates. This does, however, make it more difficult to extract deterministic trends. The results can be better represented with probabilistic confidence intervals (e.g. 95% CI) for the trendline (see Figure 3.4). The trendlines are fitted as 4th degree polynomials as this degree is necessary to reach the best fit for Rudrapur.

Besides the R-squared test (Figure 3.3 and section A.2) and the CI calculation (Figure 3.4), the

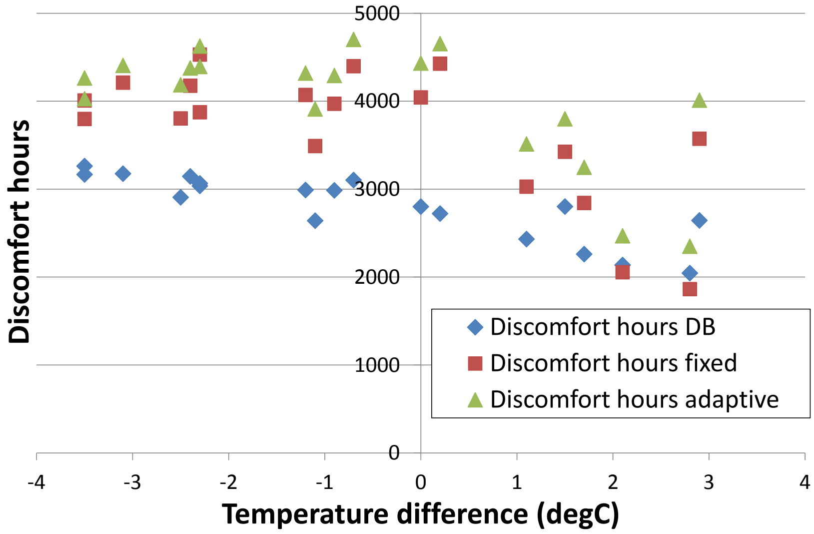

Figure 3.5: Comparison of the number of discomfort hours as resulting from *DesignBuilder* versus their calculation with a fixed or adaptive comfort zone for Chambéry.

significance of the results is evaluated using F-statistics to test a linear hypothesis on the postulated nonlinear-regression-model (NLM) coefficients. The probability (p-value) is computed for an F-test that all coefficient estimates in the assumed 4th polynomial nonlinear-regression-model are zero. Thus, it test the polynomial fit against a constant fit. The F-statistic vs constant model for the calculated fits (see Figure 3.4) are significant for all three fits: NLM CHM - p-value = 0.05, NLM RDP - p-value = 0.02, NLM BS - p-value: 0.0162. The F-statistic vs constant model is similar to a one-way analysis of variance (anova1). Data, for example for CHM, is sorted into temperature intervals with equal number of data points (-3.5°C - -3°C, -2.5°C - -2°C, -1.5°C - -0.9°C, 1.0°C - 1.7°C, 2.1°C - 3°C). This test results in a p-value of 0.066. In order to achieve equal number of points per interval certain values are neglected and the sorting in intervals does not reflect the continuous nature of the independent variable (temperature). Therefore the F-statistic vs constant model is preferable.

The size of our current data set (sample) results in wide CI limits. Therefore, the representativeness of the trend we estimate here is not statistically robust and could be misleading. This is a persistent problem when dealing with small records, and we expect to carry out further analysis of the trends with more simulations. The use of more robust techniques for calculating confidence intervals (e.g. bootstrapping) is also a potential avenue for further work. A better choice of climates, i.e. one that respects local topographical conditions better, could remove the outliers seen in our graphs. For example, we simulated two locations south of the Alps for Chambéry and they were both outliers.

Figure 3.5 shows the difference in the number of discomfort hours for the locations around Chambéry as resulting from *DesignBuilder* compared to their calculation using a fixed or an adaptive comfort zone. A fixed comfort zone means one constant comfort zone which combines the two different comfort zones with summer or winter clothes (figure 5.2.1.1 in ASHRAE (2004)). Adaptive comfort zone means a comfort zone which has for each day a comfort zone of a size similar to the summer or winter comfort zone but which moves depending on the preceding monthly average between the extremes of the summer and winter zone. The fixed comfort zone results in average over the 19 locations for Chambéry in 10% less discomfort hours due to its greater size. This difference is in general less pronounced for locations with a higher number of discomfort hours as for example Braunschweig, Germany (4530 fixed, 4627 adaptive:

2% difference) than in locations with lower numbers of discomfort hours as for example in Nimes, France (1863 fixed, 2351 adaptive: 21% difference). The more the indoor climatic states are concentrated in the comfort zone, the more hours are affected when the adaptive comfort zone is applied (see Figures 3.6 and 3.7).

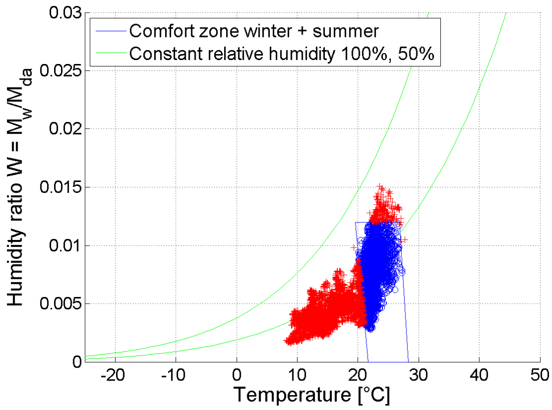

Figure 3.6: Cloud of hourly indoor climatic states in Braunschweig /Germany for the Chambéry building. The humidity ratio is given in mass water per mass dry air.

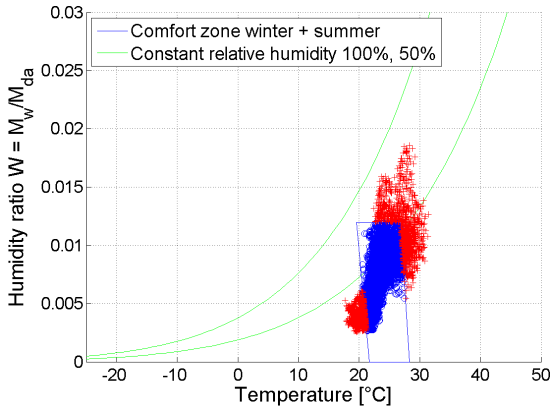

Figure 3.7: Cloud of hourly indoor climatic states in Nimes /France for the Chambéry building. The humidity ratio is given in mass water per mass dry air.

As Figure 3.5 shows, the number of discomfort hours as given by *DesignBuilder* is in average 30% lower than the number given by the adaptive calculation. *DesignBuilder* calculates comfort using the standard ASHRAE comfort zone (figure 5.2.1.1 in ASHRAE (2004)) with a clothing level of 0.5 in the summer season and 1.0 in the winter season. Uncomfortable hours are summed up per zone for occupied periods. This explains the difference to the fixed and adaptive values as those are calculated using temperature and humidity averaged over all conditioned zones and also for unoccupied periods.

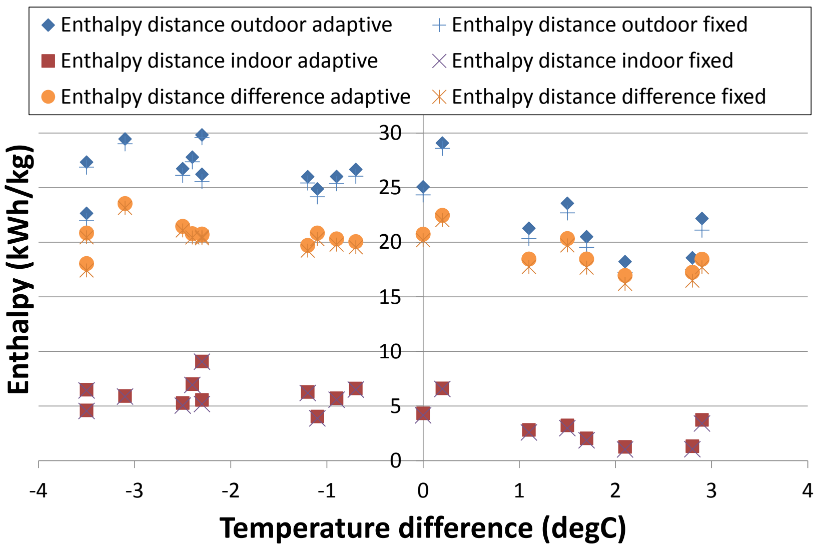

Figure 3.8: Outdoor enthalpy distance, indoor enthalpy distance and the resulting enthalpy distance difference for Chambéry.

The nearly negligible effect of assuming comfort to be adaptive is also illustrated in Figure 3.8 as the difference between the adaptive and fixed values is very small. The figure shows the enthalpy distance from the outdoor conditions to the comfort zone, the respective distance for the simulated indoor conditions and the resulting difference between those two distances (*enthalpy distance difference*). This shows that although it makes sense to use adaptive comfort (especially when dealing with natural ventilated buildings) a consideration between benefits and calculation efforts has to be found.

Figures 3.9 and 3.10 illustrate the difference between *enthalpy distance difference* and *degree day difference* as used in last semester's project. The *degree day difference* is the difference between the sum of heating and cooling degree days between outdoor and indoor conditions. It captures not only the number of hours outside the comfort zone but also their distance. However, distance is only measured one-dimensional on the temperature axis. The *enthalpy distance difference* builds on this approach but includes overly humid states as well which are neglected in the *degree day difference* approach. Thus distance is measured in two dimensions on the temperature and the humidity axis. In temperate climates humidity is not very important regarding comfort (see Figures 3.6 and 3.7). Therefore, there is nearly no difference between the normalized value of these metrics in temperate climates (Figure 3.9). This changes in hotter and more humid climates like for example India (Figure 3.10). In these conditions humidity is a significant factor (Figure 3.11) and the graph shows that the integration of this factor in the performance metric as done in the *enthalpy distance difference* makes the response curve more pronounced and descriptive. In colder conditions than the design condition performance calculated with the *enthalpy distance difference* is in general lower and in warmer conditions in general higher than when calculated with the *degree day difference* approach.

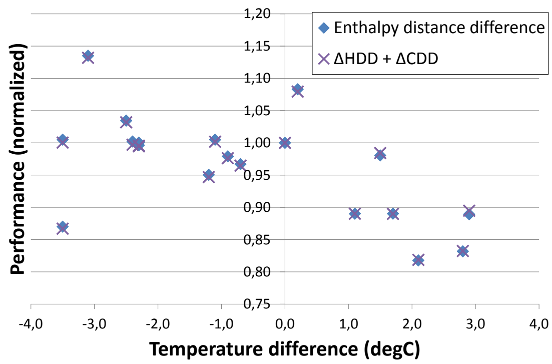

Figure 3.9: Comparison of different performance metrics for Chambéry: Enthalpy distance difference, ΔHDD+ΔCDD.

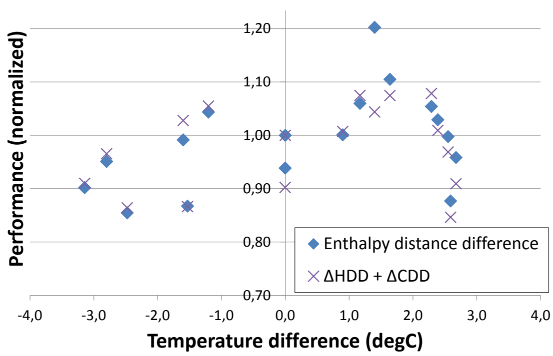

Figure 3.10: Comparison of different performance metrics for Rudrapur: Enthalpy distance difference, ΔHDD+ΔCDD.

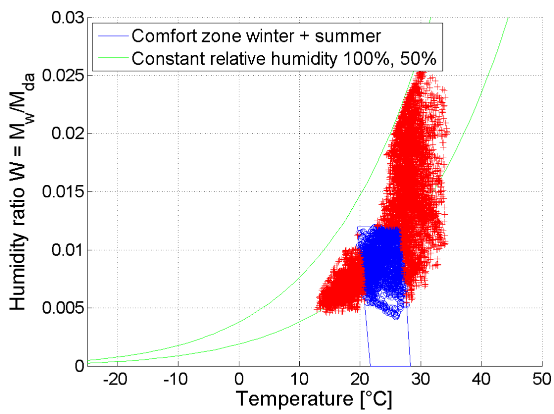

Figure 3.11: Cloud of hourly indoor climatic states in Rudrapur /India. The humidity ratio is given in mass water per mass dry air.

Chapter 4

Conclusion and future work

4.1 Conclusion

Indoor and outdoor enthalpy distances represent the magnitude as well as duration of climatic states from the edge of a comfort zone. Using the *enthalpy distances difference* as a metric seems to show a building's performance in a changing climate better than changes in uncomfortable hours or HVAC energy use. Resulting response curves contain more information than responses obtained by other metrics. This could, for example, allow a designer to explore various design options based on their robustness to climate change. Each design strategy/change could be simulated in surrounding locations to ascertain its performance (in creating a comfortable indoor environment in a changing climate) without the influence of the climate itself. The potential of the *enthalpy distance difference* is illustrated by the significant different response curves obtained for the three different building types. Furthermore, the response curve for the high performance building indicates a lower sensitivity for this building type to changing climatic conditions compared to a standard building. As hypothesized performance is peaking in the design home location.

The methodology we propose in this paper potentially covers a wide range of realistic climate change possibilities without the computational effort of a full Monte Carlo-style analysis. Extant literature suggests that the rise in global temperature predicted by GCMs (Global Climate Model) is not useful as is for building simulation for two reasons: localizing these models to the spatial and temporal resolution required for building simulation would overwhelm the computing power available for most simulation work, and the average global rise in temperature is not necessarily indicative of micro- or meso-scale changes in climate. Our methodology allows the simulation of several hypothetical climate change scenarios, but because the weather files are composed from real climate data, the auto- and inter-correlations of the weather parameters are more realistic.

There is a wide spread of data and several outliers in this study due to the paucity of data. We expect trends to become clearer with more data because the relative influence of outliers and erroneous data decreases in a larger sample size. As demonstrated by the projects discussed in the introduction, there is a balance to strike between obtaining large amounts of data through extensive computation and confidence in the results. Statistical methods like resampling can increase the coverage probability of confidence intervals without necessitating the generation of more data, though they are even further removed from the underlying physics of a building's response to its climate.

4.2 Future work

Future work includes the generation of larger datasets to base hypothesized trends on more data points and to increase the coefficient of determination. In order to do this in an efficient way, batch mode processing and the automation of the procedure have to be further developed. Batch mode processing was already used in this project (see section B.4.2) but can be improved further by implementing remote simulation on a server cluster. Batch generation of weather data it still a missing functionality in the *METEONORM* software.

Furthermore, the application of the developed *enthalpy distance difference* performance metric on more case studies and especially in the design process of buildings is necessary to gain further information about the strength and weaknesses of the developed approach. Only the adoption of the metric in actual design work gives the validation that this performance metric brings added value. Using the *enthalpy distance difference* to evaluate the design steps as applied in this project to model the high performance building (see section B.3) would be an interesting application of the methodology developed. For each design step changes in the different zones (too hot, too humid, too cold, ...) surrounding the comfort zone could be recorded using the developed metric. This would lead to a quantification of the influence of the latest design modification.

The used approach of modeling several locations with a similar mean annual temperature but otherwise different climatic parameters resulted in a wide spread of obtained performance values for these locations. Future work could follow this approach, postulate a mean annual temperature and evaluate the impact of other climatic parameters. This would be very useful to explain high observed performance differences with an identical annual temperature. Conclusions of this work could then give feedback into the design process. Work in this area, using the developed methodology of this semester's project, would be a promising follow up to last semester's project. The previous project tried to grasp the influence of different climatic parameters on a building's performance but was limited in its significance due to the sealing effect of the predominant factor temperature and insufficiently developed performance metrics. The now developed methodology could foster further research in this field.

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Appendix A

Supplements

A.1 Detailed results

	fixed comfort zone								adaptive comfort zone								fixed comfort zone						adaptive comfort zone					
Locations	hours comfortable	hours underheated	degree days underheated	hours overheated	degree days overheated	hours overhumid	overhumid ratio points	overhumid degree days	hours comfortable	hours underheated	degree days underheated	hours overheated	degree days overheated	hours overhumid	overhumid ratio points	overhumid degree days	add sensible	add sensible remove latent	remove latent	remove sens. remove latent	remove sensible	sum enthalpy	add sensible	add sensible remove latent	remove latent	remove sens. remove latent	remove sensible	sum enthalpy
'Aix-en-Provence FR'	1640	6266	2441	541	53	313	0	9	990	6818	2561	763	80	189	0	6	59458	48	1009	364	1101	61980	62272	389	698	557	1678	65595
'Bern'	888	7393	3707	167	13	312	0	10	593	7609	3786	372	35	186	0	6	90178	86	1110	447	142	91964	92069	239	749	901	445	94403
'Bologna IT'	1231	6220	2835	818	98	491	1	20	733	6720	2955	1011	136	296	1	15	69023	81	2397	3297	1203	76001	71764	601	1657	4083	1727	79832
'CHAMBERY/AIX BAINS'	971	7209	3493	233	19	347	1	15	650	7463	3578	454	44	193	0	8	84996	286	1618	409	307	87616	86873	774	950	949	705	90250
'Freiburg im Breisgau GM'	784	7472	3764	170	12	334	1	13	542	7661	3834	347	34	210	0	9	91597	204	1448	369	160	93778	93215	588	916	767	506	95992
'Genève SZ'	878	7472	3694	168	12	242	0	8	567	7701	3771	355	33	137	0	5	89881	106	848	264	206	91304	91674	330	528	578	563	93673
'Kaiserslautern GM'	708	7814	4012	88	9	150	0	5	514	7920	4060	223	22	103	0	3	97666	56	484	200	117	98523	98835	115	387	358	343	100038
'Lausanne SZ'	838	7576	3817	131	8	215	0	7	554	7787	3890	294	25	125	0	4	92861	123	714	267	75	94039	94560	391	400	562	324	96236
'Metz FR'	786	7606	3695	139	10	229	0	8	544	7794	3761	286	29	136	0	5	89980	59	929	479	93	91540	91567	196	674	793	366	93596
'Muenchen GM'	703	7813	4261	63	4	181	0	5	485	7950	4315	195	15	130	0	3	103619	222	506	43	74	104464	104866	349	381	151	300	106047
'Nimes FR'	1605	6326	2461	598	66	231	0	9	969	6847	2584	801	96	143	0	6	59924	83	1021	712	1363	63104	62865	367	722	903	2002	66858
'Saint-Etienne FR'	956	7369	3510	234	20	201	0	7	642	7571	3590	424	46	123	0	5	85424	61	780	431	293	86989	87356	148	541	823	708	89575
'Torino IT'	1113	6719	3187	336	29	592	1	26	708	7160	3291	549	55	343	1	16	77513	154	2909	680	430	81685	79831	929	1818	1471	781	84830
'Toulouse FR'	1189	6859	2752	378	37	334	1	12	736	7219	2866	612	67	193	0	7	67071	117	1315	1419	406	70327	69710	447	854	1965	845	73822
'Valence FR'	1265	6708	2870	430	46	357	1	15	756	7116	2980	671	77	217	0	9	69899	44	1606	925	702	73175	72480	366	1084	1443	1218	76591
'Alborg DA'	413	8228	4361	13	0	106	0	2	315	8296	4394	81	4	68	0	1	106147	87	220	15	7	106476	106934	141	141	108	59	107383
'Braunschweig GM'	615	7939	3952	95	8	111	0	2	418	8038	4005	226	23	78	0	2	96180	82	245	153	110	96770	97444	133	184	270	378	98410
'PARIS FR'	844	7517	3189	143	10	256	0	8	555	7738	3271	305	29	162	0	5	77706	70	828	374	108	79085	79655	225	559	719	374	81532
'Zwickau GM'	681	7798	4181	78	5	203	0	8	468	7927	4239	237	20	128	0	5	101711	49	871	263	62	102956	103102	120	558	647	268	104694
'Aix-en-Provence FR indoor_1'	6705	985	48	649	33	421	0	11	6290	1072	50	1118	67	280	0	6	1175	0	1338	560	611	3683	1213	0	786	1317	1225	4542
'Bern indoor_1'	4886	3163	683	402	14	309	0	9	4365	3181	683	1106	72	108	0	3	16592	0	1047	829	183	18650	16596	0	456	1956	1012	20020
'Bologna IT indoor_1'	5187	2081	208	1050	72	442	1	14	4748	2195	210	1535	123	282	0	7	5064	0	1870	4694	621	12250	5103	1	941	6212	1182	13439
'CHAMBERY/AIX BAINS indoor_1'	4717	3342	504	149	5	552	1	22	4326	3429	505	673	33	332	0	10	12252	0	2469	127	77	14925	12294	0	1424	1421	454	15593
'Freiburg im Breisgau GM indoor_1'	4362	3885	877	28	1	485	1	19	4057	3975	879	398	15	330	1	12	21328	0	2029	66	4	23428	21371	0	1496	746	180	23793
'Genève SZ indoor_1'	4789	3486	773	60	1	425	0	12	4467	3534	773	511	22	248	0	5	18780	0	1268	19	24	20090	18794	0	746	690	345	20575
'Kaiserslautern GM indoor_1'	4584	3929	997	22	1	225	0	6	4382	3986	999	247	10	145	0	3	24236	0	651	62	5	24954	24283	0	412	387	141	25223
'Lausanne SZ indoor_1'	4956	3284	689	241	8	279	0	8	4573	3314	689	742	45	131	0	3	16743	0	917	331	151	18143	16753	0	416	1138	697	19004
'Metz FR indoor_1'	4689	3694	854	46	1	331	0	11	4440	3764	856	354	15	202	0	5	20781	0	1376	135	1	22293	20821	0	802	868	147	22638
'Muenchen GM indoor_1'	4549	3873	833	4	0	334	0	8	4353	3941	835	207	6	259	0	6	20242	0	883	0	1	21125	20294	0	719	188	108	21308
'Nimes FR indoor_1'	6897	851	33	734	41	278	0	8	6409	948	35	1196	80	207	0	6	805	0	1021	1254	687	3767	842	0	751	1745	1418	4756
'Saint-Etienne FR indoor_1'	5270	3079	520	92	2	319	0	11	4848	3219	524	543	25	150	0	4	12648	0	1222	50	26	13947	12731	0	598	874	347	14550
'Torino IT indoor_1'	5335	2275	252	400	17	750	1	31	4960	2289	252	1111	59	400	1	12	6128	0	3750	589	247	10714	6131	0	1905	2849	740	11625
'Toulouse FR indoor_1'	5917	2121	153	237	8	485	1	16	5511	2232	155	697	35	320	0	9	3715	0	1959	976	50	6700	3777	0	1177	2054	349	7357
'Valence FR indoor_1'	5732	2221	261	356	15	451	1	18	5246	2373	264	900	50	241	0	7	6347	0	2050	700	196	9293	6410	0	1132	1951	640	10133
'Alborg DA indoor_1'	4230	4341	1326	0	0	189	0	4	4133	4388	1327	93	2	146	0	3	32251	0	376	0	0	32627	32270	0	304	91	28	32693
'Braunschweig GM indoor_1'	4752	3793	933	9	0	206	0	4	4496	3883	935	245	8	136	0	3	22692	0	447	4	1	23144	22736	0	297	220	129	23383
'PARIS FR indoor_1'	4962	3395	617	4	0	399	1	13	4732	3471	618	288	9	269	0	7	15024	0	1341	9	0	16374	15048	0	917	525	83	16573
'Zwickau GM indoor_1'	4333	4099	921	2	0	326	0	12	4105	4200	922	278	9	177	0	4	22371	0	1250	0	0	23621	22402	0	661	660	111	23835

Figure A.1: Results Chambéry, (un)comfortable hours in hours, degree days in K x d, sensible, latent heat and enthalpy in kj/kg

Locations	fixed comfort zone								adaptive comfort zone								fixed comfort zone						adaptive comfort zone					
	hours comfortable	hours underheated	degree days underheated	hours overheated	degree days overheated	hours overhumid	overhumid ratio points	overhumid degree days	hours comfortable	hours underheated	degree days underheated	hours overheated	degree days overheated	hours overhumid	overhumid ratio points	overhumid degree days	add sensible	add sensible remove latent	remove latent	remove sens. remove latent	remove sensible	sum enthalpy	add sensible	add sensible remove latent	remove latent	remove sens. remove latent	remove sensible	sum enthalpy
'Allahabad IN'	1311	1852	379	4749	1043	848	3	64	772	2399	490	4940	1074	649	2	57	9250	100	10447	80491	6015	106303	11660	1580	9295	80699	6631	109865
'Bhilwara IN'	1732	1990	423	4502	1000	536	2	43	995	2640	563	4683	1029	442	2	38	10312	0	6538	38283	13026	68159	13663	743	5945	38305	13719	72374
'Bhind IN'	1396	2253	538	4478	1057	633	2	52	838	2779	649	4660	1088	483	2	44	13146	90	8575	63368	8188	93366	15593	1559	7429	63429	8907	96918
'Bilaspur IN'	1653	1220	178	4383	838	1504	6	144	932	2045	315	4671	884	1112	5	119	4335	116	21500	43682	9241	78875	7250	3768	17318	44763	10029	83128
'Dehradun IN'	1368	3270	865	2447	341	1675	6	148	815	4175	996	2748	388	1022	4	104	21083	190	20133	27527	2448	71380	23480	5665	14450	28803	3132	75529
'Haldwani-cum-Kathgodam IN'	1400	2985	773	3105	524	1270	4	107	860	3703	895	3305	559	892	4	86	18858	138	15345	36217	3789	74348	21296	3817	12097	36468	4480	78156
'Hardwar IN'	1249	2975	778	3212	557	1324	5	122	758	3636	891	3400	591	966	4	101	18960	167	17753	45045	2925	84850	21192	3740	14748	45368	3546	88594
'ISLAMABAD PK'	1328	3614	1155	3013	600	805	2	55	817	4201	1269	3176	632	566	2	45	28153	56	7720	30216	5844	71990	30582	2115	6216	30346	6534	75793
'Kota IN'	1661	1934	386	4231	907	934	4	85	948	2732	535	4419	944	661	3	65	9428	9	12840	40472	12192	74941	12825	2884	10111	40741	12951	79512
'Pali IN'	1742	1807	364	4818	1173	393	1	27	997	2414	507	4978	1199	371	1	26	8870	0	3893	43614	13706	70083	12340	237	3732	43614	14332	74255
'Pathankot IN'	1239	3179	957	3501	785	841	3	65	764	3760	1077	3652	816	584	2	53	23351	63	9206	48644	5773	87037	25875	2144	7619	48798	6432	90868
'Peshawar PK'	1348	3636	1157	3032	619	744	2	52	824	4274	1277	3186	651	476	2	39	28198	107	7771	33757	5334	75166	30655	2266	6173	33852	6054	78999
'Rudrapur'	1465	2426	576	4381	1010	488	1	34	841	2960	683	4563	1037	396	1	31	14093	10	5651	62446	6220	88419	16592	656	5207	62489	6848	91791
'Bhopal IN'	1879	1747	302	3744	728	1390	5	130	1050	2725	463	4053	777	932	4	93	7385	20	17936	26930	10642	62913	10931	3995	13066	28389	11469	67852
'Godhra IN'	1794	1347	207	4829	937	790	3	75	974	2073	358	4997	970	716	3	71	5070	0	12078	49903	9017	76068	8706	1092	11089	49928	9778	80593
'Nagpur IN'	1608	1147	161	4550	917	1455	6	142	911	1956	298	4773	961	1120	5	122	3942	71	19273	47897	10121	81304	6911	3575	15594	48563	10906	85549
'Udaipur IN'	1721	1964	400	4132	849	943	4	87	971	2774	554	4341	888	674	3	70	9765	0	12619	32993	11502	66879	13217	2620	10050	33375	12286	71548
'Allahabad IN indoor_1'	2055	1551	148	3963	343	1191	4	103	1324	2272	220	4077	349	1087	4	100	3629	0	26774	46215	1118	77735	5363	276	26451	46342	1217	79649
'Bhilwara IN indoor_1'	2762	1801	158	3340	304	857	4	87	1904	2627	263	3375	305	854	4	87	3845	0	13600	22728	2968	43141	6406	150	13452	22728	3004	45741
'Bhind IN indoor_1'	2062	1892	192	4139	452	667	2	54	1405	2451	254	4261	459	643	2	53	4688	0	12368	47926	2471	67453	6212	65	12274	47976	2623	69150
'Bilaspur IN indoor_1'	2954	396	15	3198	299	2212	9	226	1762	1577	83	3421	310	2000	9	208	374	0	32781	23368	2682	59204	2000	1065	30346	24915	2767	61093
'Dehradun IN indoor_1'	2203	2645	347	2172	149	1740	6	152	1646	3055	387	2534	175	1525	5	131	8466	0	23697	19921	505	52590	9443	156	21328	22388	738	54054
'Haldwani-cum-Kathgodam IN indoor	2259	2429	305	2699	222	1373	5	120	1644	2897	352	2935	236	1284	5	116	7440	0	19032	26652	899	54023	8586	578	18093	27137	1101	55494
'Hardwar IN indoor_1'	1878	2505	314	3104	282	1273	4	107	1323	2922	361	3354	295	1161	4	102	7684	0	18319	38629	706	65338	8829	175	17901	38980	915	66800
'ISLAMABAD PK indoor_1'	2024	3544	744	2042	154	1150	3	81	1242	4362	823	2130	158	1026	3	77	18143	0	13070	17700	901	49814	20029	960	12186	17730	993	51897
'Kota IN indoor_1'	2690	1588	124	3169	290	1313	6	137	1761	2456	219	3314	299	1229	5	127	3018	0	22002	22898	3217	51135	5349	615	20552	23813	3321	53650
'Pali IN indoor_1'	2713	1622	139	4070	421	355	1	28	1721	2564	256	4120	422	355	1	28	3380	0	6535	31576	3375	44867	6236	0	6535	31576	3418	47765
'Pathankot IN indoor_1'	1879	2961	521	2939	299	981	3	70	1290	3517	582	3056	306	897	3	68	12713	0	11185	37923	1124	62946	14177	236	10894	38064	1273	64645
'Peshawar PK indoor_1'	2101	3380	668	2344	204	935	2	54	1334	4112	736	2463	213	851	2	51	16298	0	9442	25569	894	52203	17929	490	8916	25677	1075	54087
'Rudrapur indoor_1'	2181	2118	257	3986	437	475	1	31	1494	2722	325	4087	443	457	1	31	6273	0	7920	49132	1523	64848	7938	6	7880	49194	1645	66663
'Bhopal IN indoor_1'	3159	1299	83	2068	182	2234	9	220	1960	2542	190	2267	191	1991	8	195	2023	0	26881	10126	2373	41402	4597	3394	22542	11279	2455	44267
'Godhra IN indoor_1'	3295	680	30	3484	277	1301	6	144	1948	1977	125	3572	281	1263	6	140	729	0	24127	26534	1722	53113	3037	715	23399	26586	1786	55524
'Nagpur IN indoor_1'	2899	334	12	3324	308	2203	10	233	1700	1451	75	3521	318	2088	9	220	294	0	33072	23350	3002	59718	1829	962	31184	24383	3107	61465
'Udaipur IN indoor_1'	2782	1511	114	3057	270	1410	6	149	1815	2409	204	3214	278	1322	6	139	2772	0	21750	16380	3103	44006	4975	583	20830	16787	3221	46397

Figure A.2: Results Rudrapur, (un)comfortable hours in hours, degree days in K × d, sensible, latent heat and enthalpy in kj/kg

	fixed comfort zone								adaptive comfort zone								fixed comfort zone						adaptive comfort zone					
Locations	hours comfortable	hours underheated	degree days underheated	hours overheated	degree days overheated	hours overhumid	overhumid ratio points	overhumid degree days	hours comfortable	hours underheated	degree days underheated	hours overheated	degree days overheated	hours overhumid	overhumid ratio points	overhumid degree days	add sensible	add sensible remove latent	remove latent	remove sens. remove latent	remove sensible	sum enthalpy	add sensible	add sensible remove latent	remove latent	remove sens. remove latent	remove sensible	sum enthalpy
'Alborg DA'	413	8228	4361	13	0	106	0	2	315	8296	4394	81	4	68	0	1	106147	87	220	15	7	106476	106934	141	141	108	59	107383
'Boras SW'	243	8427	4947	0	0	90	0	2	222	8435	4956	39	2	64	0	1	120317	71	185	0	0	120573	120552	82	125	84	11	120853
'Braunschweig GM'	615	7939	3952	95	8	111	0	2	418	8038	4005	226	23	78	0	2	96180	82	245	153	110	96770	97444	133	184	270	378	98410
'CHAMBERY/AIX BAINS'	971	7209	3493	233	19	347	1	15	650	7463	3578	454	44	193	0	8	84996	286	1618	409	307	87616	86873	774	950	949	705	90250
'Freiburg im Breisgau GM'	784	7472	3764	170	12	334	1	13	542	7661	3834	347	34	210	0	9	91597	204	1448	369	160	93778	93215	588	916	767	506	95992
'Gdansk PL'	434	8130	4385	9	0	187	0	6	324	8218	4421	85	4	133	0	4	106625	390	612	12	2	107642	107420	507	419	186	49	108581
'Kaiserslautern GM'	708	7814	4012	88	9	150	0	5	514	7920	4060	223	22	103	0	3	97666	56	484	200	117	98523	98835	115	387	358	343	100038
'Kirkcaldy UK'	18	8742	5254	0	0	0	0	0	18	8742	5254	0	0	0	0	0	127900	0	0	0	0	127900	127900	0	0	0	0	127900
'Koeln GM'	663	7769	3625	113	7	215	0	7	478	7896	3686	254	24	132	0	4	88268	123	752	240	103	89486	89691	291	468	560	360	91370
'Metz FR'	786	7606	3695	139	10	229	0	8	544	7794	3761	286	29	136	0	5	89980	59	929	479	93	91540	91567	196	674	793	366	93596
'Muenchen GM'	703	7813	4261	63	4	181	0	5	485	7950	4315	195	15	130	0	3	103619	222	506	43	74	104464	104866	349	381	151	300	106047
'PARIS FR'	844	7517	3189	143	10	256	0	8	555	7738	3271	305	29	162	0	5	77706	70	828	374	108	79085	79655	225	559	719	374	81532
'ZAGREB HR'	1146	6529	3043	625	68	460	1	19	662	6982	3158	866	108	250	0	10	74034	79	2309	3082	779	80284	76631	680	1313	4032	1345	84002
'Zwickau GM'	681	7798	4181	78	5	203	0	8	468	7927	4239	237	20	128	0	5	101711	49	871	263	62	102956	103102	120	558	647	268	104694
'Alborg DA indoor_1'	2444	6068	2658	54	2	194	0	4	2083	6097	2661	524	27	56	0	1	64664	0	410	62	23	65159	64749	0	117	550	419	65835
'Boras SW indoor_1'	2222	6385	3148	8	0	145	0	3	2057	6426	3149	218	8	59	0	1	76513	0	299	5	1	76817	76547	0	93	295	102	77036
'Braunschweig GM indoor_1'	2645	5716	2244	234	11	165	0	3	2138	5842	2254	714	52	66	0	1	54588	0	336	243	170	55337	54842	0	63	778	908	56590
'CHAMBERY/AIX BAINS indoor_1'	2791	4813	1772	839	61	317	0	11	2113	4885	1777	1673	154	89	0	2	43118	0	1349	1953	897	47317	43242	0	387	3700	2310	49638
'Freiburg im Breisgau GM indoor_1'	2584	5378	2109	424	22	374	1	14	2010	5483	2117	1141	86	126	0	4	51292	0	1643	861	269	54065	51489	0	790	2290	1199	55768
'Gdansk PL indoor_1'	2283	6023	2644	50	1	404	0	10	1858	6108	2652	569	27	225	0	5	64302	0	1149	45	14	65510	64483	0	581	835	388	66286
'Kaiserslautern GM indoor_1'	2837	5527	2242	219	14	177	0	5	2282	5618	2249	803	58	57	0	1	54531	0	528	400	190	55650	54700	0	140	1092	943	56875
'Kirkcaldy UK indoor_1'	656	8104	3173	0	0	0	0	0	656	8104	3173	0	0	0	0	0	77195	0	0	0	0	77195	77195	0	0	0	0	77195
'Koeln GM indoor_1'	2470	5737	2031	216	10	337	0	11	2024	5847	2043	785	52	104	0	3	49441	0	1158	140	212	50952	49717	0	402	1193	881	52193
'Metz FR indoor_1'	2803	5385	2038	338	19	234	0	7	2149	5478	2045	1051	78	82	0	1	49602	0	829	1058	181	51669	49776	0	208	2188	1063	53236
'Muenchen GM indoor_1'	2687	5607	2343	163	7	303	0	8	2155	5686	2349	796	47	123	0	2	56955	0	893	75	153	58075	57098	0	320	921	823	59161
'PARIS FR indoor_1'	2864	5275	1703	291	12	330	0	10	2206	5468	1712	976	63	110	0	2	41486	0	1109	409	186	43189	41689	0	286	1640	962	44577
'ZAGREB HR indoor_1'	2215	4515	1676	1871	226	159	0	5	1802	4609	1680	2273	337	76	0	2	40749	0	656	7603	2752	51760	40843	0	269	8942	4461	54515
'Zwickau GM indoor_1'	2645	5665	2397	198	8	252	0	7	2106	5787	2405	798	52	69	0	1	58281	0	863	513	113	59770	58479	0	188	1602	716	60985

Figure A.3: Results Braunschweig, (un)comfortable hours in hours, degree days in K x d, sensible, latent heat and enthalpy in kj/kg

A.2 Enthalpy distance difference trendlines

- Braunschweig:

$$y = 0,0053x^4 - 0,0002x^3 - 0,046x^2 - 0,0357x + 1,0455$$

$$R^2 = 0,709$$

- Chambéry:

$$y = -0,0001x^4 + 0,0007x^3 - 0,0052x^2 - 0,0332x + 0,978$$

$$R^2 = 0,4701$$

- Rudrapur:

$$y = -0,0046x^4 - 0,0114x^3 + 0,0253x^2 + 0,081x + 0,9881$$

$$R^2 = 0,5833$$

Appendix B

Modeling

B.1 General settings for all buildings

In the following general settings which are mostly the same for all investigated building types are listed. Those settings are necessary to apply the same settings of a free running building for all three buildings. Only changes from the default settings are noted. The differences between the buildings are geometry and facade composition and not stated here.

B.1.1 Model options

Data

- HVAC: simple, Auxiliary energy calculations 0-None, Mechanical ventilation method 2 - Ideal loads
- Natural ventilation: calculated, Infiltration units 4-n50 (ac/h at 50Pa), Airtightness method 2-Crack template

Heating Design

- Calculation options: Temperature control 2-Operative temperature

Cooling Design

- Calculation options: Temperature control 2-Operative temperature
- Solar: Solar distribution Chambery 3 - Full interior and exterior (necessary due to the trombe wall), Rudrapur, Vechelde 2-Full exterior, uncheck: Check for non-convex zones?

Simulation

- Calculation options: Timesteps per hour 4 (necessary for calculated natural ventilation), Temperature control 2-Operative temperature
- Solar: Solar distribution Chambery 3 - Full interior and exterior (necessary due to the trombe wall), Rudrapur, Vechelde 2-Full exterior, uncheck: Check for non-convex zones?

B.1.2 Model taps

Activity

- Environmental control: Heating setpoint temperature 19°C, Heating set back 16°C, Cooling setpoint temperature 25°C, Cooling set back 28°C, Ventilation setpoint temperature 23,4°C

Construction

- Airtightness: Crack template Chambery Excellent, Vechelde, Rudrapur medium

Openings

- External Windows: Operation, Glazing area opens 25%, Operation schedule On (The timing of opening is calculated in the simulation according to cooling and fresh air requirements.)
- Doors: External, Area door opens 50%, Time door is open 5%; Internal, Area door opens 50%, Time door is open 30%

HVAC

- HVAC Template: Auxiliary energy (kWh/m2) 0,00, Compact Type 5-CAV, Natural Ventilation On, Mixed mode on, Mechanical Ventilation on, Rate (ac/h) 0,7, Economizer 1-none, Heat Recovery off, Heating, cooling off
- Mechanical Ventilation: On, Outside air definition method 1 by zone, Outside air (ac/h) 0.7, Schedule On, Economizer 1-None
- Heating, Cooling off
- Natural Ventilation: On
  - Mixed mode on
  - Advanced: Control mode schedule - Always 4, Min outdoor ventilation air schedule - Always 0.6
  - Options: Control mode 2-temperature

B.2 Chambery specific settings

B.2.1 Layout

- Modeling building according to defined geometry of a residential building as given for the IBPSA modeling competition 2013.
- Care has to be taken to follow the conventions for block and zone dimensions, Zone height = block height (full volume is taken into account), thickness of walls and floors is predefined (Model options data - Data - Zone volume calculations)

- Check: compactness. The given geometry is a very compact form with a good ratio of volume to surface. This makes this building especially suitable for the passive house approach of which the compact form is a basic principle. (BRE, 2012)
- Orientation: balcony to the south. A further basic principle is to face the longest facade to the south to make optimal use of solar gains. As the given building is quadratic, no facade is more suitable than the others. In general it would be necessary to have a more detailed knowledge of the building site to evaluate the shading of surrounding buildings and trees and the necessity of windows in certain directions to guarantee a special view. (Grondzik et al., 2009; Sei, 2007) As no further information is given the surrounding is assumed to be homogeneous without shading. Finally the building is placed with the balcony facing south due to the given internal layout as such that rooms for which the availability of sunlight is critical (family rooms and bedrooms) are facing south (BRE, 2012; Sei, 2007).

B.2.2 Activities

Model Options

Data - Gains Data Early (Internal gains are separated into various categories). The data cannot be entered as 'lumped' (combination of internal gains into one value). Comfort calculations (internal temperatures, air change, different comfort indexes, etc.) are only executed in EnergyPlus when the 'PEOPLE' statement is used which is not the case with lumped gains.

Data - Timing Schedules: Schedules have to be used as otherwise the use of 'compact' HVAC data would not be possible. In this model only 'simple' HVAC data is used, but for further use 'compact' HVAC might be necessary to implement for example heat recovery. This would not be possible with 'simple' HVAC design. Also, it is only possible to use the predefined gain with detailed compact schedules.

When creating 'compact' schedules care has to be taken about the order of days (Sunday to Saturday). Also the *WinterDesignDay* and *SummerDesignDay* statement has to be made before the *AllOtherDays* statement.

Activity Template

For each type of room a template is created which combines schedules for gains and occupancy, different values for gains, as well as different setpoints. All zones for which no gains are specified (corridor, hall, storeroom, toilets) are set via template as conditioned but without gains. In order to apply standard internal gains, gains as specified for the IBPSA modeling competition are used.

Occupancy

Density (people/m$_2$) Using the maximum gain in the respective zone and the floor area a maximal area specific load is calculated (W/m$_2$). The quotient of load over metabolic heat results in the required occupancy density (people/m$_2$).

Schedule Transforming gain values into a fraction to the maximum in the respective zone. These fractions are used in compact schedules. Both for internal as well as occupancy schedule the winter and summer design days are chosen as the days with the lowest and respectively highest gains.

Metabolic

Activity - Metabolic Heat (W/person) A generic metabolic heat of 100 W/person is chosen. The metabolic heat gain represents the total heat gain per person including convective, radiant, and latent heat.

Metabolic factor The metabolic factor (0.85 for women, 0.75 children) is set to 1.

Environmental control

Heating Setpoint Temperatures According to the predefined specifications the heating setpoint temperature is set to 19°C and the set back temperature to 16°C. Those temperatures are only relevant when the building is equiped with a heating system.

Ventilation Setpoint Temperatures/ Natural ventilation Setpoint temperature natural ventilation cooling: *23.4 °C*. From this temperature onward natural cooling is enabled.

Miscellaneous - Lumped internal gains due to lighting and appliances

As the given heat gains include lighting and all other appliances present in a single family, house office equipment and domestic hot water are switched off whereas the general lighting energy demand is set to 0 W/m2 -100lux (Lighting tab). This means general lighting is still on (to be able to perform daylighting calculation), but without any consumption. As the lighting electricity consumption is included in the lumped gains, the consumption of lighting is independent of the selected target illuminance. That is why the target illuminance in lux is assumed to default room specific templates.All gains except for occupancy gains are summed up in miscellaneous gains (combination of maximum gain and schedule).

Hot water demand is assumed according to default room specific templates.

Load (W/m$_2$) Calculation of the area specific gain with the quotient of the maximum gain over the floor area in the respective zone.

Schedule Transforming gain values into a fraction to the maximum in the respective zone. These fractions are used in compact schedules.

B.2.3 Construction

Envelope consistency due to the Passive House Standard (BRE, 2012).

Construction elements first run

Table B.1: External wall composition.

	Material	U-Value	Thickness
Outermost layer	External plastering	0.350	0.015m
	Thermal insulation	0.040	0.30m
	Lime-sand brick	0.990	0.175m
Innermost layer	Internal plastering	0.700	0.01m
U - Value		0.127 W/(m^K)	0.50m

(Passivhaus Institut, 2000a; Passivhaus Institut, 2000b)

Table B.2: Internal wall composition.

	Material	**U-Value**	**Thickness**
Outermost layer	Plasterboard	0.350	0.025m
	Air		0.02m
Innermost layer	Plasterboard	0.350	0.025m
U - Value		0.794 W/(m^K)	0.50m

Table B.3: Ground slab composition.

	Material	**U-Value**	**Thickness**
Innermost layer	Screed	1.200	0.04m
	Thermal insulation	0.040	0.30m
Outermost layer	Reinforced concrete	2.100	0.14m
U-Value		0.129 W/(m^{2}K)	0.48m

According to: Passivhaus Institut (2000a); Passivhaus Institut (2000b). The internal floor is similar with reduced thermal insulation.

Table B.4: Semi exposed ceiling composition.

	Material	**U-Value**	**Thickness**
Outermost layer	Thermal insulation		0.41m
Innermost layer	Concrete		0.14m
U-Value		0.082 W/(m^{2}K)	0.55m

Airtightness

Model Options/ Data/ Natural ventilation Natural ventilation: *Calculated*. Infiltration units: *n50 (ac/h at 50 Pa)* - has to be smaller than 0,6 ac/h at 50 Pa (BRE, 2012). This setting is only relevant for the design of the heating and cooling system. The actual rate is calculated. Airtightness method: *Crack template*. When using calculated natural ventilation, the airtightness of the building is not predefined but is calculated through a crack template.
Help: `http://www.designbuilder.co.uk/helpv3.2/#_Calculated_ventilation_data_detail11.htm#kanchor1885`

Construction tab data Infiltration rate: *0,3* (for design only) - is calculated using crack template. Due to the compact form of the building and the fact, that actual passive building achieve an airtightness in this magnitude (Schnieders, 2003). Crack template: *Excellent* Passive houses have to be designed and constructed with great care to ensure the required airtightness (Passivhaus Institut, 2000a).

B.2.4 Openings

External windows

Glazing type - Requirements for windows (Passivhaus Institut, 2000a)

- Glazing with $U_g <= 0{,}8$ W/(m^{2}K)
- Highly insulated frame, U_f between 0,5 and 0,7 W/(m^{2}K)
- Avoidance of thermal bridges between glazing and frame

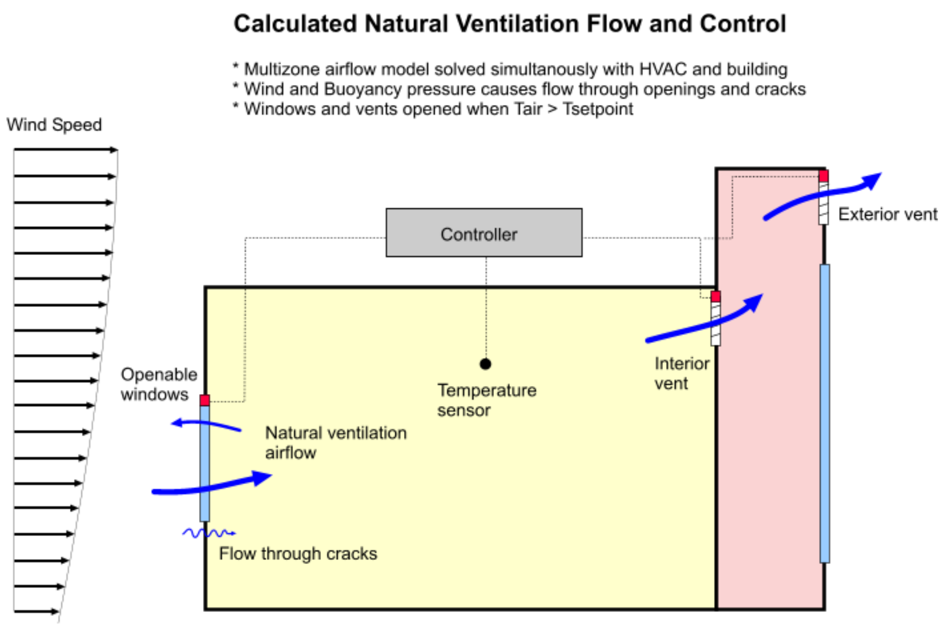

Figure B.1: Calculated natural ventilation. (DesignBuilder Software Limited, 2013)

- Good solar transmittance g >= 0.5 to make optimum use of solar gains in winter (BRE, 2012)
- –> Chosen glazing type (Openings data): Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg; Total solar transmission (SHGC): 0,47, U-Value (W/m^2-K): 0,786

Layout The glazing of passive houses is in central Europe optimized at the south facade with glazing ratios historically in excess of 50%. Modern glazing systems are able to reduce this ratio to 25-35%. Minimal glazing is applied to the north facade (BRE, 2012; Sei, 2007).

Figures B.2 and B.3 show the relationship between heating demand and heat load as found in a parametric study on the first passive house building in Germany (Schnieders, 2003). The building has a ratio of glazing area to facade of 0.3 (window area to facade: 0.4). Given this ratio and an initially fixed U-value of the windows of 0.85 W/m^2 the insulation of the walls and floors is fixed as such that the building has a maximal heating load of 10 W/m^2. This value is important for passive houses as buildings with a heat load in that magnitude do not require a separate heating system. All the required heat is in general supplied by internal gains and solar gains or if necessary through a small preheating system of the supply air. Figures B.2 and B.3 illustrate the important effect of the thermal transmittance

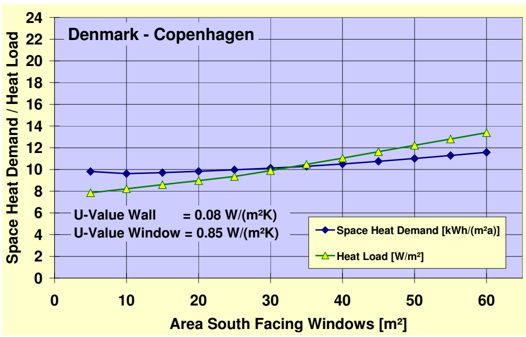

Figure B.2: Heating demand dependent on window area (Schnieders, 2003)

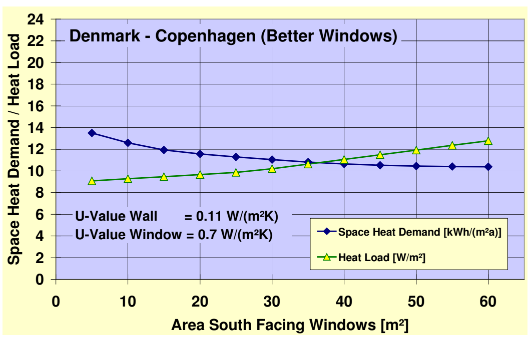

Figure B.3: Heating demand dependent on window area (better windows) (Schnieders, 2003)

(U-value) on the heating demand. In the building with the lower insulated windows the losses through the increased glazing area are increasing faster than the corresponding gains, thus leading to an increasing space heat demand. The opposite takes effect in the building with the higher insulated windows. The losses are lower than the gains, decreasing total heating demand. Locations with higher solar radiation during the heating period, as Germany (see respective example in Schnieders (2003)) and Chambery show a decreasing heating demand with increasing window area already with the less insulated windows. But with more and more window area the savings in total heating demand become less and less whereas the maximal required heating load increases faster. Given the chosen level of wall insulation and window transmittance a ratio of south facing glazing of 0.35 seems appropriate for the initial design of the high performance building in this project. As a first approximation for east and west walls 20% glazing are chosen and for north walls 10%.

Shading In a first approximation fixed shading is installed over the south facing windows of the ground and first floor.

Operation Glazing area opens: 25% (operable window area as a fraction of the total window area) Operation schedule: As the given heating schedule (reduction of heating temperature during unoccupied periods of the weekdays) reflects the general occupancy, this schedule is also used as the schedule for the operation schedule for the glazing operation. The schedule consists only of the values 1 (heating to setpoint temperature) and 0.5 (access set back temperature).
Help: `http://www.designbuilder.co.uk/helpv3.2/#_Operation2.htm`

Natural ventilation in the calculated mode takes always place when first the indoor temperature is greater than the outdoor temperature and second the indoor temperature is greater than the natural ventilation setpoint temperature (Activity/ Environmental control) and third the schedule value of the glazing operation schedule is greater than zero. Thus, by using the given heating schedule, natural ventilation by opening the windows can only take place in occupied periods.
Help: `http://www.designbuilder.co.uk/helpv3.2/#_Natural_ventilation_modelling.htm`

B.2.5 HVAC

Model Options

Advanced/ Natural Ventilation/ Calculated/ Modulate opening areas Those settings are also accessible under HVAC/ Natural Ventilation/ Options. The modulation of openings takes into account the fact that in buildings with manually operated windows, the windows are probably not fully opened when the outdoor air is much colder than the indoor air. Thus the modulation of openings starts at a specified temperature difference decreasing the opening area from the maximum opening area (specified in B.2.4), up to a specified minimum fraction of the opening area at a specified maximum temperature difference (see Figure B.4). This option is not activated first as it also prevents ventilation in summer when the indoor temperature is very hot and thus exists a relatively high temperature difference to the moderate outdoor temperature. Help: `http://www.designbuilder.co.uk/helpv3.2/#Natural_Ventilation.htm`

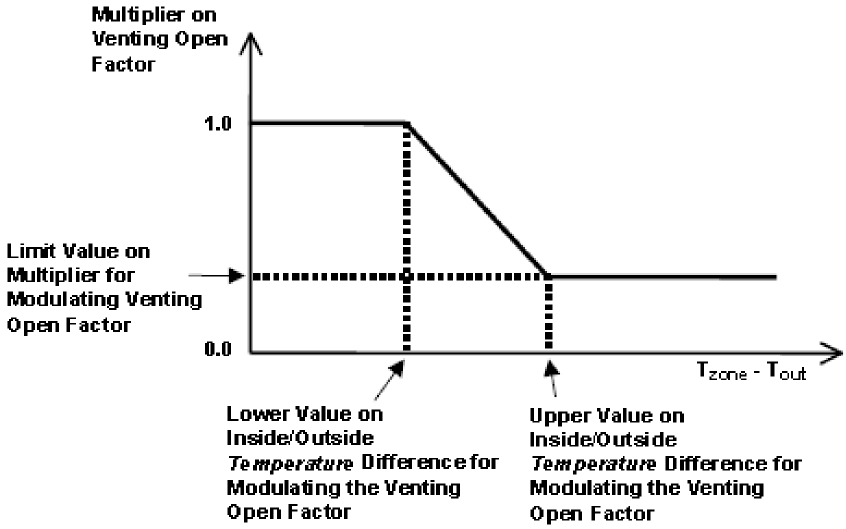

Figure B.4: Modulation of openings (DesignBuilder Software Limited, 2013).

Mechanical ventilation

Natural ventilation serves always to purposes: 1. provide fresh air, 2. cool a building. In order to simulate a natural ventilation system of this kind a combination of natural and mechanical ventilation is chosen. As for the mechanical ventilation the auxiliary energy consumption is set to 0 (no electricity consumption by fans and pumps) this is not heating the building and is not influencing the buildings electricity consumption. Thus it is not a real mechanical ventilation system which is implemented in the building, but only a representation for the fresh air provision part of natural ventilation. If only natural ventilation is used, no ventilation takes place when the room temperature is lower than the set point temperature for natural ventilation cooling. Thus natural ventilation by itself is only providing cooling and not a constant fresh air stream. This can be simulated by adding constant mechanical ventilation up to the required air changes per zone (0.7 ac/h).

Help: `http://www.designbuilder.co.uk/helpv2/Content/Outside_Air.htm`

Natural Ventilation

Help: `http://www.designbuilder.co.uk/tutorials/calculated_natvent/`

Model options Scheduled ventilation is used when the approximate ventilation rates are known. Calculated natural ventilation is used when there is no ventilation data for the building.

Outside air definition method The outside air definition method (air changes per hour) and the operation schedule are not used in the simulation for calculated natural ventilation. They are still displayed as they are used for Heating and Cooling Design calculations.

Control mode '*DB: 2-Temperature - all of the zone's openable windows and doors are opened if Tzone > Tout and Tzone > Tset and operation schedule allows venting. 3-Enthalpy - All of the zone's openable windows and doors are opened if Hzone > Hout and Tzone > Tset and operation schedule allows venting.*'(DesignBuilder Software Limited, 2013)

Help: `http://www.designbuilder.co.uk/helpv3.2/#Natural_Ventilation.htm`

Mixed mode

As described in B.2.5 the natural ventilation consist of one part for cooling (temperature controlled - the *natural ventilation*) and another part to ensure the fresh air provision (always 0.7 ac/h - the *mechanical ventilation*). Mixed mode is applied to avoid parallel usage of the two parts which would result during summer in an unrealistic high cooling, as it would be the calculated possible natural ventilation plus the forced 0.7 ac/h (see Figure B.5.

Help: `http://www.designbuilder.co.uk/helpv3.2/#MixedMode.htm`

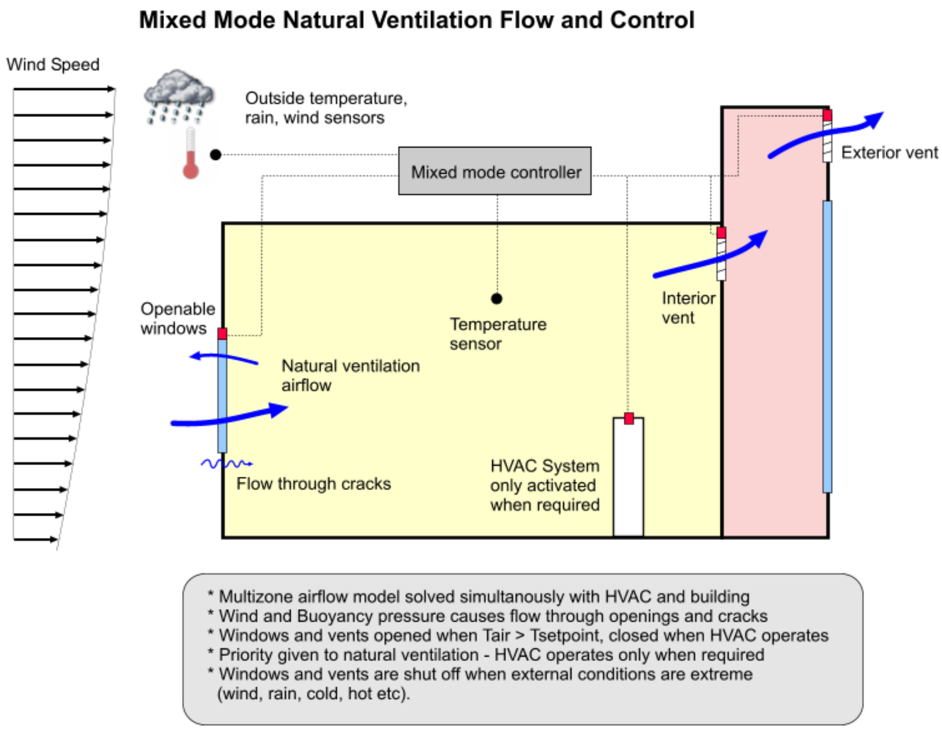

Figure B.5: Mixed mode natural ventilation. (DesignBuilder Software Limited, 2013)

B.2.6 Lighting

The schedule for lighting (although not relevant for the gains) is set to the room specific occupancy schedule. Lighting control is witched on (Lighting tab - Lighting control) using the stepped type with two steps (simulating artificial lighting which can be controlled in two steps - two lamps).

B.3 Modeling steps

- Modification of ratio between insulation and thermal mass Sei (2007), p. 22
- Modification of glazing area
- Trombe wall - Adding solar gain
  A trombe wall consists of glass with high transmission, an air gap 15cm, an absorber layer (copper) and a 30cm high mass partition. The partition represents the 30cm high mass wall (although only drawn as a typical 7cm partition). In one block all partitions are drawn with the same thickness.

However, this value is only influencing the geometry of the room and is not included in the thermal calculations. Thermal calculations take into account the wall composition and this parameter can be modified for every wall element individually.
Help: `http://www.designbuilder.co.uk/helpv3.2/#Trombe_Walls.htm?Highlight=trombewall`

- Adding shading
- Modifying ventilation schemes (ventilation of trombe wall, night flush ventilation)
- Further possible modifications - Adding phase change materials (PCMs)
  This a newly implemented option in *DesignBuilder* 3.2 and is reported to be beneficial in balancing temperature (Campbell, 2011; Grondzik et al., 2009).
  - Significant increase in thermal comfort in dry and marine climates.
  - Not suited for very hot climates.
  - PCMs with a melt temperature of 25°C results in the highest results.

B.4 Methodological aspects of the modeling process

B.4.1 Weather data

Weather data is taken from *Meteonorm* (Remund et al., 2012a) for the interpolated locations in *energy plus* format (.epw). In order to use this data in *DesignBuilder* the data has to be converted (Tools - Hourly Weather data - Convert).

B.4.2 Parallel simulations - batch mode

- The current *DesignBuilder* beta version 3.2 allows multiple simulations to be queued from within DB. To access this functionality, use the 'Batch' tab of the Simulation options dialog (Simulation/Batch). Check 'Use job server'. This loads the simulation in the simulation manager which can be accessed by the 'Batch job' icon. Once the simulations are finished, you can load results from the simulation manager.
- *DesignBuilder* can be closed or other .dsb files can be opened without interrupting the simulations. To retrieve results, the .dsb file used to start the simulation has to be opened. Go to the Simulation tab and click on the 'Batch jobs' toolbar icon.
- In order to access the job server to change its settings, *DesignBuilder* has to be executed as administrator.
- The following links help setting up a different job sever than a local one, for example on an external cluster.
  `http://www.iesd.dmu.ac.uk/~jeplus/wiki/doku.php?id=docs:db_plugin`
  `http://www.iesd.dmu.ac.uk/~jeplus/wiki/doku.php?id=docs:check_db_jobserver`
- The *DesignBuilder* simulation manager submits jobs to a local jobserver in the background. The jobserver runs jobs in only one place which is the `C:\Users\XXXXXX\AppData\Local\DesignBuilder\JobServer\Jobs` 'EnergyPlus' folder. The original 'EnergyPlus' folder from *DesignBuilder* runs jobs

on the local computer. If the jobs should run on another server, like for example the DMU cluster (see links above), this folder has to be replaced.

- Simulations can be accelerated by making use of multiple threads through parallel processing. This is possible with EnergyPlus 7.1 (provided with *DesignBuilder* v3.0.0.146 and later). The 'Maximum number of threads' to be used by EnergyPlus on the EnergyPlus tab of the Program options dialog can be increased (according to the calculation power of the computer) to make use of these capabilities.

B.4.3 Optimization

- Program help: `http://www.designbuilder.co.uk/helpv3.2/#OptimisationCalculations.htm`
- *DesignBuilder* webinar: `http://www.designbuilder.co.uk/content/view/135/206/` `http://www.designbuilder.co.uk/downloadsv1/optimisation_webinar1/`
- *DesignBuilder* design competition: `http://www.iesd.dmu.ac.uk/~adopt/wiki/doku.php?id=competition:submissions`
- *DesignBuilder* design competition winning entry: `https://sites.google.com/site/just4architecture/blog/design-optimization-competition-2012`

Appendix C

Weather data

C.1 Input

- Places (cities, towns, villages): Shapefile of predefined locations and cities for which (interpolated) *Meteonorm* climatic data is available. Made available by Remund et al. (2012a). *Meteonorm* can generate interpolated climatic data for every geographical location.
- Other alternatives for places: Open Street Map (OSM)
  Format: shapefile (points)
  Using a query for example from following sites:
  `http://www.faveve.uni-stuttgart.de/~troll/OSM/osm-poll.cgi?format=gpx&filename=cities&query=[place=city][bbox=-30,30,30,60]`
  `http://open.mapquestapi.com/xapi/api/0.6/node[place=city][bbox=-30,30,30,60]`
  The bounding box (bbox) goes from left-bottom to right-top. The disadvantage is that the maximum size of the bounding box is only 10°. Another possibility is the download of the full map in the required region, for example from `http://download.geofabrik.de/` and the extraction of the required data by a database system (for example *postgreSQL*)
- Borders of countries: `http://thematicmapping.org/downloads/world_borders.php`
  Format: shapefile (polygons)
- Climatic data: Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978 (WorldClim, 2005).
  Format: rasterfile (geotiff)
  The high resolution climatic datasets are published in tiles of 30° square. The finest resolution available is 30 arcseconds, which means each degree consists of 120 pixels squared.
  - BIO1 = Annual Mean Temperature
  - BIO7 = Temperature Annual Range (P5-P6), P5 = BIO5 = Max Temperature of Warmest Month, P6 = BIO6 = Min Temperature of Coldest Month
- Solar radiation data (CCAFS, 2000)

C.2 GIS handling

1. All geoalgorithms are called via the Sextante plug-in from within Quantum GIS (QGIS). Thus it is possible to store the complete data handling process in one model including a flow of different geoalgorithms.

2. As the region in question consists of two tiles of the rastered climatic data (WorldClim, 2005), the tiles are merged via the geoalgorithm «Saga/ Grid tools/ Merge raster layers», Raster -Miscellaneous.
3. Using the plug-in «1-Band Raster Colour Table V1.x» a specific detailed color map is created to make fine temperature variations visible.
4. Conversion from avc into tiff: «Raster/Conversion/Translate».
5. Masking of worldwide radiation data to area of temperature tiles: «Saga/ Grid-Tools/ Grid Masking».
6. Due to several layer in the project it can be advantageous to toggle rendering manually to avoid unnecessary calculation time. Right-click on the layer list and checking «Update drawing order» establishes the correct layer order.
7. In order to select only cities greater than 100'000 inhabitants, a query is used on the places - shapefile: «Qgis geoalgorithms/ Vector selection tools/ Select by attribute».
8. To avoid overly crowded maps at lower zoom levels the labeling is adjusted to be dependent on the scale.
9. For information purposes a «special action» is allocated to the cities which opens on demand the respective Wikipedia page for a selected city.
   For example: `C:\ProgramFiles(x86)\Google\Chrome\Application\chrome.exehttp://en.wikipedia.org/wiki/[\%"NAME"\%]`
10. The specific climatic data for each city (Annual mean temperature, temperature annual range) is allocated to each city by integrating the attributes of the underlying climatic raster layers into its attributes: «Saga/ Shapes/ Grid/ Add grid values to Points».
11. Draw contour lines for temperature plot at specific temperature levels: «GRASS/ Raster/ r.contour».
12. Using only two contour lines around the annual mean temperature of the city in question (+- 2,5°C) a temperature buffer zone is drawn: «GRASS/ Raster/ r.contour». Example for Chambery/France: As the annual mean temperature of the investigated location is 11,1°C, contour lines are drawn at 8,6°C and 13,6°C.
13. The two different contour lines are each selected «Qgis geoalgorithms/ Vector selection tools/ Select by attribute» and saved in two different shapefiles. The contours are colored differently to mark the upper and the lower temperature difference of the investigated location.
14. Using these upper and lower temperature difference levels cities are selected which are close to those contour lines and have thus a annual mean temperature more or less 2.5°C higher or lower than the location in question. In order to be aware of different patterns in the annual temperature development, the temperature seasonality is also taken into account. The selected cities are saved into their own shapefile: «Scripts/ Save selected features».

C.3 Temperature contour maps

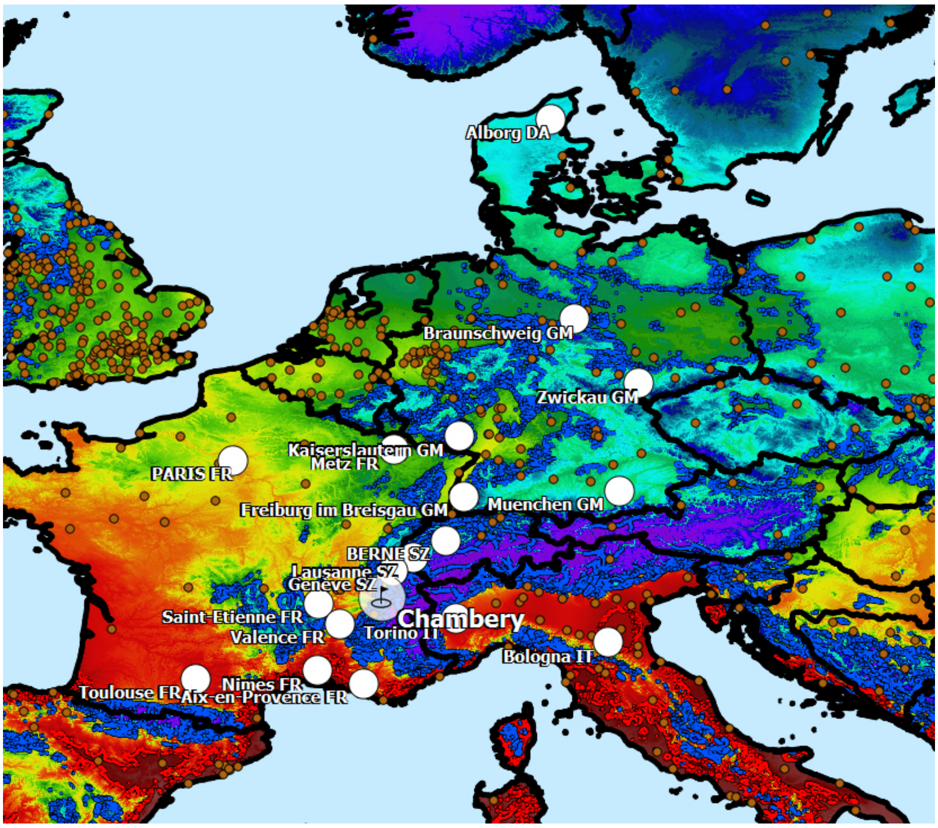

Figure C.1: Temperature contour map of Chambery

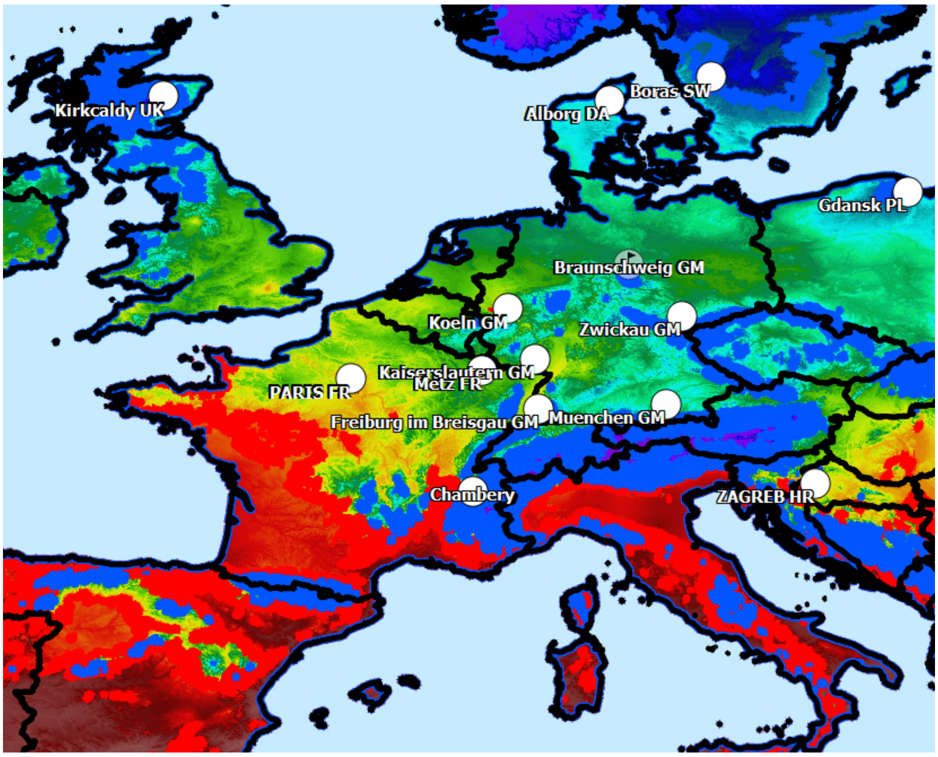

Figure C.2: Temperature contour map of Braunschweig

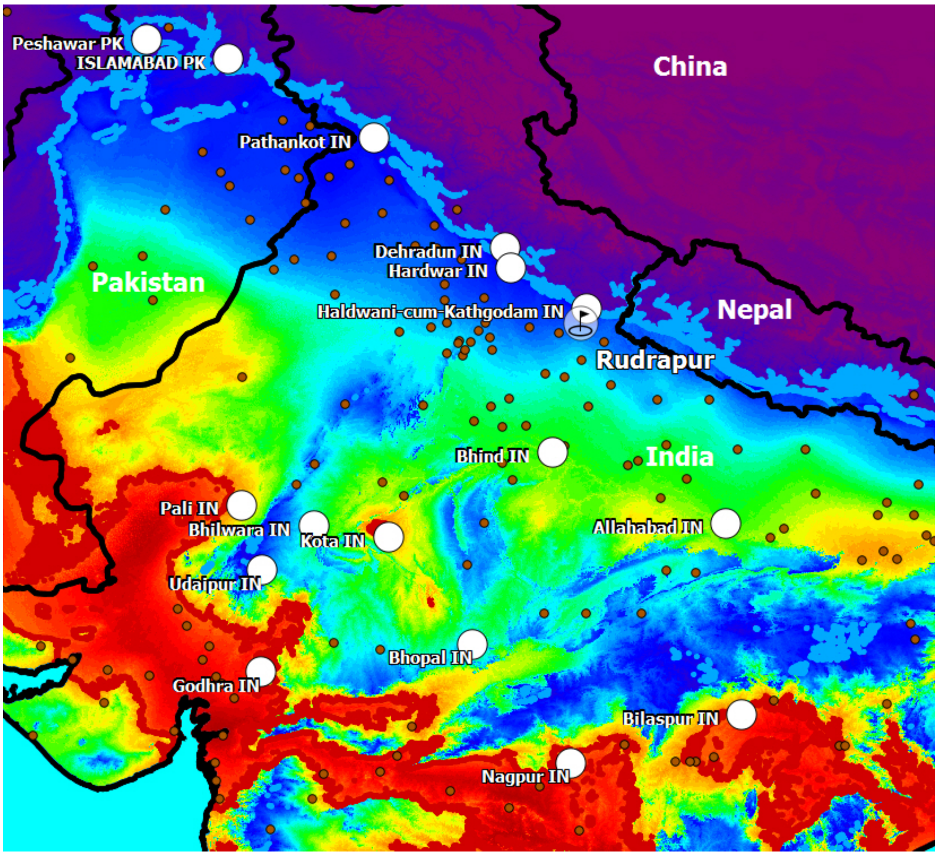

Figure C.3: Temperature contour map of Rudrapur

Appendix D

Attachments

- *DesignBuilder* models of the Chambery, Braunschweig and Rudrapur building
- *DesignBuilder* Analysis summary for the three building types including the input data
- Matlab script to calculate performance metrics (uncomfortable hours, degree days, enthalpy distance)
- Response curves and Matlab script to fit trendlines and to evaluate their significance
- GIS data
- Literature collection